AFTAC-TR-80-24

HIGH RESOLUTION SPECTRA OF HE DETONATIONS

HSS Inc
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Bedford, MA 01730

7 JULY 1980

Final Report (1 October 1978 - 14 October 1979)

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFTAC-TR-80-24	2. GOVT ACCESSION NO.: AD-A087415
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): HIGH RESOLUTION SPECTRA OF HE DETONATIONS	5. TYPE OF REPORT & PERIOD COVERED: Final Report, 1 Oct 1978 – 14 Oct 1979
	6. PERFORMING ORG. REPORT NUMBER: HSS-B-060
7. AUTHOR(s): D. F. HANSEN	8. CONTRACT OR GRANT NUMBER(s): F08606-77-C-0024, MIPR-FY7625-77-0-0052
9. PERFORMING ORGANIZATION NAME AND ADDRESS: HSS Inc, 2 ALFRED CIRCLE BEDFORD, MA 01730	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: FY7625-77-00052/T/7507, ETR, Amend 6.
11. CONTROLLING OFFICE NAME AND ADDRESS: 1035 TCHOG/TNS, PATRICK AFB FL 32925	12. REPORT DATE: 7 Jul 1980
	13. NUMBER OF PAGES: 91
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): DCASMA, Boston, 666 Summer St, Boston, Ma. 02210	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Spectrograph
High Explosive
Optical Spectroscopy
Black Body Radiation
Optical Measurement

390794

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A feasibility test was performed using optical spectroscopy to quantify the elements present in a device having a high explosive detonation. Because the heat from the explosion was about 2500°K after a few milliseconds, only the lowest excitations were observed in the elements. The presence of Al, Ti, Mn and Fe was detected within the narrow bandwidths of the instruments. A spin-off experiment using special film suggested that shrapnel could be sized even while heated and burning in flight.

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ACKNOWLEDGEMENTS

The program described in this report was sponsored by the Air Force Technical Applications Center under Contract No. F08606-77-C-0024. The measurements were conducted at a Sandia Laboratory test facility located outside of Albuquerque, NM. The cooperation and assistance of many Sandia Laboratory personnel must be recognized here, that of Mr. Wayne Sebrell is singled out in particular.

Capt. Tom Majchrowski, the AFTAC Test Director, demonstrated his concern for the success of the spectrograph program during the operational period by his attention to the instrument status and to achieving optimum operational conditions. Maj. Charles Allen, Technical Monitor for AFTAC, collaborated in defining and optimizing the instrument plan. His technical perception, advice and understanding of the problems encountered along the way helped to improve the program in many ways.

Mr. Albert Tuttle and Mr. Vincent Logiudice of HSS Inc must be recognized as having implemented the instrument plan. They performed the instrument modifications and assembled all the equipment which was done on an extremely short time scale. At the test site they worked long hours both day and night to install, align and focus the instruments.

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1. INTRODUCTION

This is a final report on the high resolution optical spectroscopy of two HE detonations conducted for the Air Force Technical Applications Center. A primary objective of theprogram was an evaluation of the capability of high resolution spectroscopy to identify the various atomic species released as a result of the explosive process acting upon component materials in the vicinity of the high explosive material.

The first event in which the high resolution spectrographs were employed by HSS Inc took place on 15 November 1978. An unfortunate malfunction in the Sandia Corp. timing system led to a premature detonation of the device. As a result no high resolution spectra were obtained.

The second event occurred at 0546 local daylight time on 14 June 1979. The same instruments were employed: three spectrographs and a boresight camera. Details of the instrument characteristics and the manner in which they were modified and deployed on Event 1 are given in Section 2. No changes in instrumentation were made for Event 2 except for the addition of a Wratten - .2 filter to the boresight camera. The instrument plan for Event 2 is given in Appendix A. The results described in this report are those obtained on Event 2. A qualitative analysis of the data was performed as described in Section 5. Recommendations for improvements in this diagnostic technique on possible future events are given in Section 6.

2. INSTRUMENTATION

2.1 Background

An exploratory program such as the present one does not warrant the developments of expensive specialized instruments if existing instruments can be adapted to the task. As a rule however, existing instruments seldom offer the capabilities of an instrument which would be developed for a specific application and in all probability lack one or more desirable features. What is important, however, is that they have enough capability to demonstrate the feasibility of the technique under investigation. Dedicated instruments more suited to the task can then follow if feasibility is demonstrated.

The three high resolution spectrographs employed by HSS Inc were developed for field use on another DoD program which had similar measurement goals but where the phenomena under study were quite different in nature. Time scales were longer and source temperatures were hotter for longer periods of time.

In contrast to field instruments high resolution spectrographs made for laboratory applications normally occupy a good fraction of a large room. They have poor relative apertures (f/number) because the lack of sensitivity can be offset by long exposures to steady state laboratory sources. Their large size is a result of two factors: (1) an extensive wavelength coverage (e.g. 3000 Å to 9000 Å), and (2) the use of long focal length optics to achieve high linear dispersion (and the desired high resolutions). Thus, high resolution laboratory instruments are seldom used for field measurements except in cases of extreme emergency or when the source characteristics permit. Time resolution is extremely difficult to achieve in these instruments.

The ARIES instruments developed by HSS Inc compromised wavelength coverage to maintain high spectral resolution, good f/number, and modest time resolution while achieving a considerable reduction in size and weight. The reduced wavelength coverage meant that the most important spectral regions had to be identified and targeted for use on any given application. Shifting of spectral regions is accomplished by a rotation of the diffraction grating and if necessary a change in the order sorting filter.

In the particular application for which the ARIES instruments were developed their size and weight were dictated by the restrictions of a sophisticated tracking mount which was assigned to their use. Reduction in size and weight of the instrument was a result not only of limited wavelength coverage but the use of higher spectral orders (a technique which lends itself most readily to instruments where wavelength coverage is restricted).

The inter-relation of the important grating and instrument parameters and the demand upon them to produce high resolution can be readily seen from a study of the dispersion relation. The dispersion equation is arrived at by differentiating the normal grating equation

$$m \lambda = a (\sin \varphi + \sin \varphi') \qquad (1)$$

where:

- m = Spectral order (1, 2, 3------)
- λ = Wavelength (Angstroms)
- a = Groove spacing (in Angstroms)
- φ = Angle of incidence
- φ' = Angle of diffraction

Upon differentiation with respect to the angle of diffraction we get

$$\frac{\partial\lambda}{\partial\varphi'} = \frac{a}{m} \cos \varphi' \qquad \text{Å/radian} \tag{2}$$

If we multiply both sides of this dispersion relation by 1/f where f is the focal length of the camera lens (or mirror) we get

$$D_\lambda = \frac{1}{f} \frac{\partial\lambda}{\partial\varphi'} = \frac{a}{mf} \cos \varphi' \qquad \text{Å/mm} \tag{3}$$

where the reciprocal linear dispersion D_λ is measured in Å/mm if the focal length is also measured in mm.

Spectrocopists almost universally use the term reciprocal linear dispersion when they compare the resolution capabilities of instruments. More often than not they abbreviate the expression to linear dispersion or just dispersion. Once upon a time it was called the plate factor.

The smaller the value of reciprocal linear dispersion the better the spectral resolution capability of the instrument. For example, if $D_\lambda = 5$ Å/mm and if the photographic image quality of the instrument and film combination were $R = 20$ line pairs/mm then the spectral resolution $\Delta\lambda$ would be

$$\Delta\lambda = D_\lambda \cdot \frac{1}{R} \tag{4}$$

$$\Delta\lambda = \frac{5}{20} = 0.25 \text{ Å}$$

Referring now to Equation 3 we can see various ways for making D_λ as small as possible: (1) choose the focal length, f, as long as possible (one can only go so far in this direction since the instrument size increases with increased focal length), (2) choose the groove spacing, a, as small as possible (again one runs into a restriction, in this case the groove spacing can not be less than $\lambda/2$), (3) choose the grating order, m, as large as possible, (4) choose the angle of diffraction, φ', as small as possible (but φ' is no longer available as a parameter that we can vary once we have fixed all the other parameters including wavelength which are related by the grating equation, (see Equation 2)

HSS Inc had some prior experience taking spectra of high temperature multi-element sources with instruments which had dispersions ranging from 5 Å/mm to several hundred Å/mm. The results of previous efforts had led us to conclude that the ARIES instruments must have dispersions of the order of 5 Å/mm if they were to perform their mission, i.e. species identification in the presence of continuous and multi-element line radiation. At a dispersion of 50 Å/mm, for example, only the strongest lines of elements present in great abundance in the source can be distinguished above the continuum; the multitude of other spectral lines of all elements present in the source are blended indistinguishably into the continuum. The choice of 5 Å/mm for the original ARIES missions applies quite appropriately to their present application on H. E. detonation where the source is highly contaminated with molecular radiations and where it turns out, there is a sparsity of high resolution spectral work reported in the literature to use for guidance.

Table 1 summarizes the characteristics of the three ARIES spectrographs in their original design configurations and as they were

TABLE 1. CHARACTERISTICS OF THE ARIES SPECTROGRAPHS AS USED ON HULA HOOP

OPTICAL DATA

Objective Lens:	Schneider Tele-Xenar f/5.5; 500 mm f.l.
Field Lens:	Off-Axis Plano-Convex; 203 mm f.l.; 38 mm diameter
Littrow Lens:	Bausch & Lomb Type I Aerial; f/6.0; 24 inch f.l.
Camera:	Flight Research Model IVC 35mm Multi data Camera; Format is standard 18.3 x 24.0mm

COMPONENT	ARIES I	ARIES II	ARIES III
Grating	B&L Replica	B&L Replica	B&L Replica
Grooves:	1200 g/mm	600 g/mm	600 g/mm
Blaze λ:	1.0μ	1.6μ	1.25μ
Blaze θ :	36° 52'	28° 41'	22° 2'
Dispersion Å/mm	4.95	5.60	8.24
Slit Width:	25μ	25μ	25μ
Silt Height:	20mm	20mm	20mm
Spectral Range (Approximately) Single Setting	120 Å	145 Å	200 Å
Wavelength Coverage (Å)	5290-5410	4200-4345	3870-4100
Internal Magnification	1:1	1:1	1:1
Grating Working Order	2	4	3
Spectral Resolution (30 lp/mm)	0.17 Å	0.19 Å	0.27 Å

first employed. We see that not very high grating orders coupled with modest groove densities were able to achieve the necessary high dispersions. Compact instrument sizes were also achieved (as demonstrated in Figure 1 which is a picture of ARIES II). The instrument is 49inches long 9 inches wide and 9 inches high. ARIES I and III differ from ARIES II only in the gratings and order sorter filters used.

We should point out that the purpose of using three instruments instead of one was to get as much wavelength coverage as possible given the size and weight restrictions of the mount. Film size,frame rates, and available film transport mechanisms entered into a performance trade-off of three vs two (or one) instruments to provide the same wavelength coverage. We elected to go with the 35mm film size because cameras with that size film and frame rates appropriate to the mission were available from G. F. E. inventory.

2.2 Application of ARIES Spectrographs to HE Detonation

An HE detonation of 50 lbs. to 100 lbs. in size behaves as a high temperature ($T > 3000°K$) radiator for only a few milliseconds. Subsequently the temperature (as indicated by Sandia Corp. brightness temperature measurements)drops to between 2500°K to 2000°K for a period lasting for about 50 milliseconds. Initial material velocities can be as high as 10,000 ft/second.

Under the above conditions the ARIES spectrographs seem inappropriate to the task. The sensitivity of the instruments, even with high speed film, is such that it can record only down to black body temperatures like 2500°K with exposure times of 18 milliseconds. The Flight Research recording cameras can be operated at a maximum frame rate of 80 frames/second, corresponding to an interframe time of 1/80 seconds

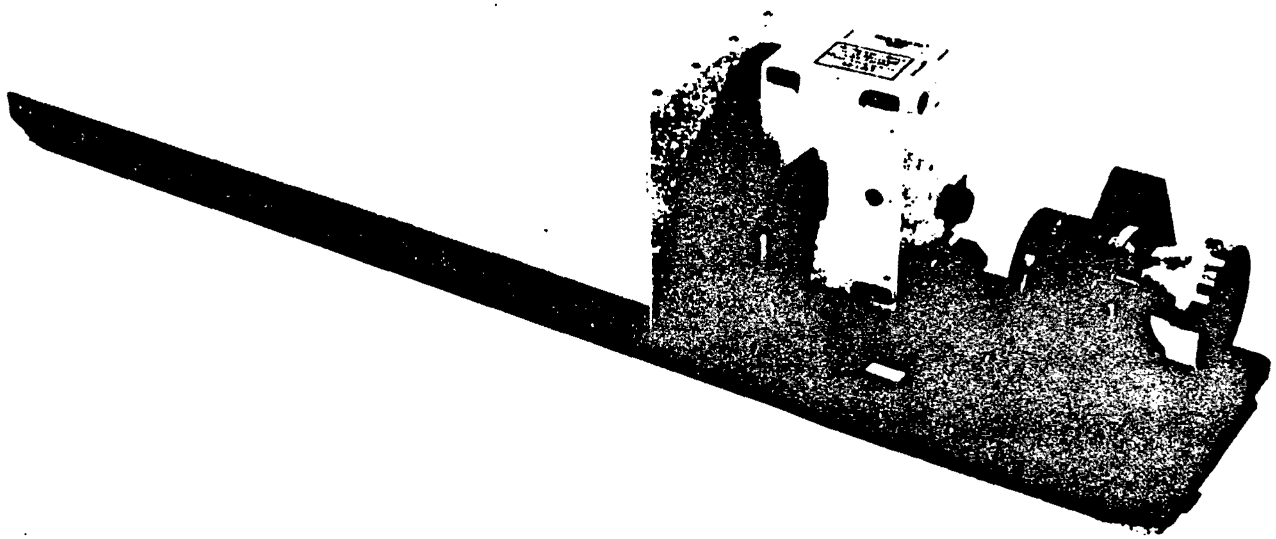


Figure 1. Picture of the ARIES II high resolution spectrograph showing also the objective lens, order sorting filter (just ahead of the entrance slit) and the Flight Research IVC cine camera.

or 12.5 milliseconds. Maximum opening of the sector shutter is 130 degrees so that the 12.5 millisecond interframe time is divided into an open (exposure) time of $\frac{130}{360}$ x 12.5 = 4.5 msec, and a closed (transport) time of $\frac{230}{260}$ x 12.5 = 8.0 msec.

Periodic malfunctions occur if these cameras are operated at 80 fps. Experience has shown that to minimize failure it is best to operate them at 20 fps or 40 fps. A comparison of interframe and exposure times at the various frame rates is as follows (assuming a maximum sector shutter opening of 130°).

Frame Rate (fps)	Interframe Time (msec)	Exposure Time (msec)	Transport Time (msec)
80	12.5	4.5	8.0
40	25.0	9.0	16.0
20	50.0	18.1	31.9

We note from the above summary that regardless of frame rate there is a 2 to 1 probability of the shutters being closed during the few milliseconds time period when the HE fireball temperature is high enough to produce recordable densities on the film. Frame rates of 300 fr/sec (or greater) would be required to guarantee at least one exposure during the brief high temperature phase of the explosion.

Each of the ARIES spectrographs was modified or adapted in a different manner to circumvent the problems outlined above. The techniques employed will be outlined below. The spectral regions which were covered by each of the instruments were selected by AFTAC from information supplied by HSS Inc. The process went as follows:

AFTAC supplied HSS Inc with a list of elements of interest to them; HSS Inc then furnished AFTAC the approximate coverage to be expected from each instrument and a pictorial display of the spectrum of each element indicating only the most prominent lines which might be expected to record. AFTAC then indicated their choice of the most desirable spectral regions to be covered by each of the instruments, these were:

INSTRUMENT	WAVELENGTH COVERAGE
ARIES III	3900 Å - 4100 Å
ARIES II	3950 Å - 4100 Å
ARIES I	4575 Å - 4700 Å

The redundant coverage by ARIES III and ARIES II instruments requires explanation. A high priority objective of the program is to look outside the fireball region with one of the instruments to attempt to record the spectra of glowing fragments as they pass through the field of view of the instrument. That mission was assigned to ARIES II. Since many elements of interest are in the spectral region from 3950 Å to 4100 Å it was necessary to assign similar coverage to ARIES III which looked directly at the fireball. ARIES I also viewed the fireball directly.

A variety of calculations were made to select those instrument parameters which would achieve optimum results and to predict the instrument performance. Several assumptions regarding source characteristics were invoked in predicting the performance since there is no prior experience with high resolution spectrographs applied to HE explosions to use for guidance. The results of those calculations are summarized in Figures 2 through 4.

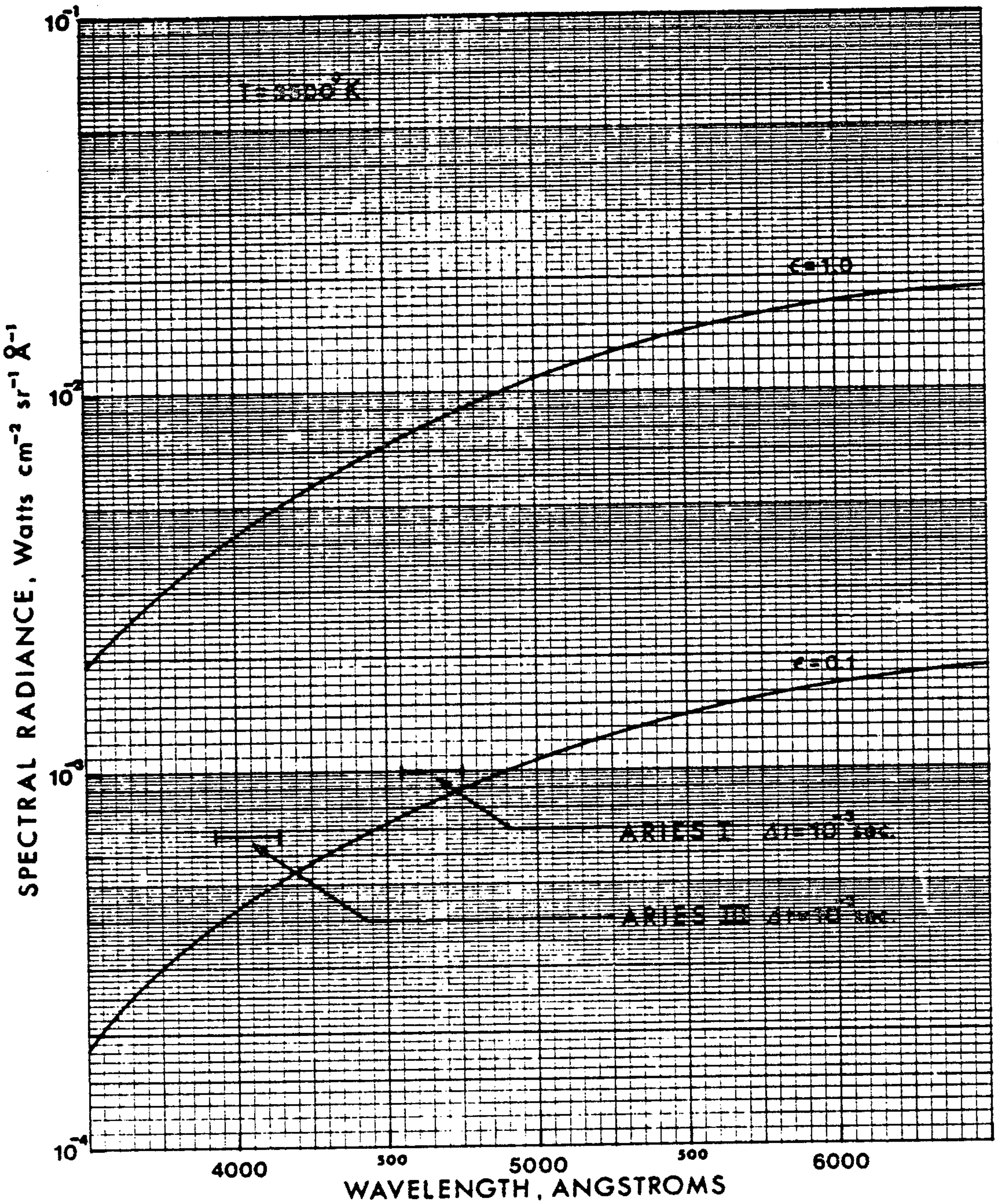


Figure 2. ARIES I and III threshold sensitivities superimposed on black body radiation curves for T = 3500 °K and two values of emissivity.

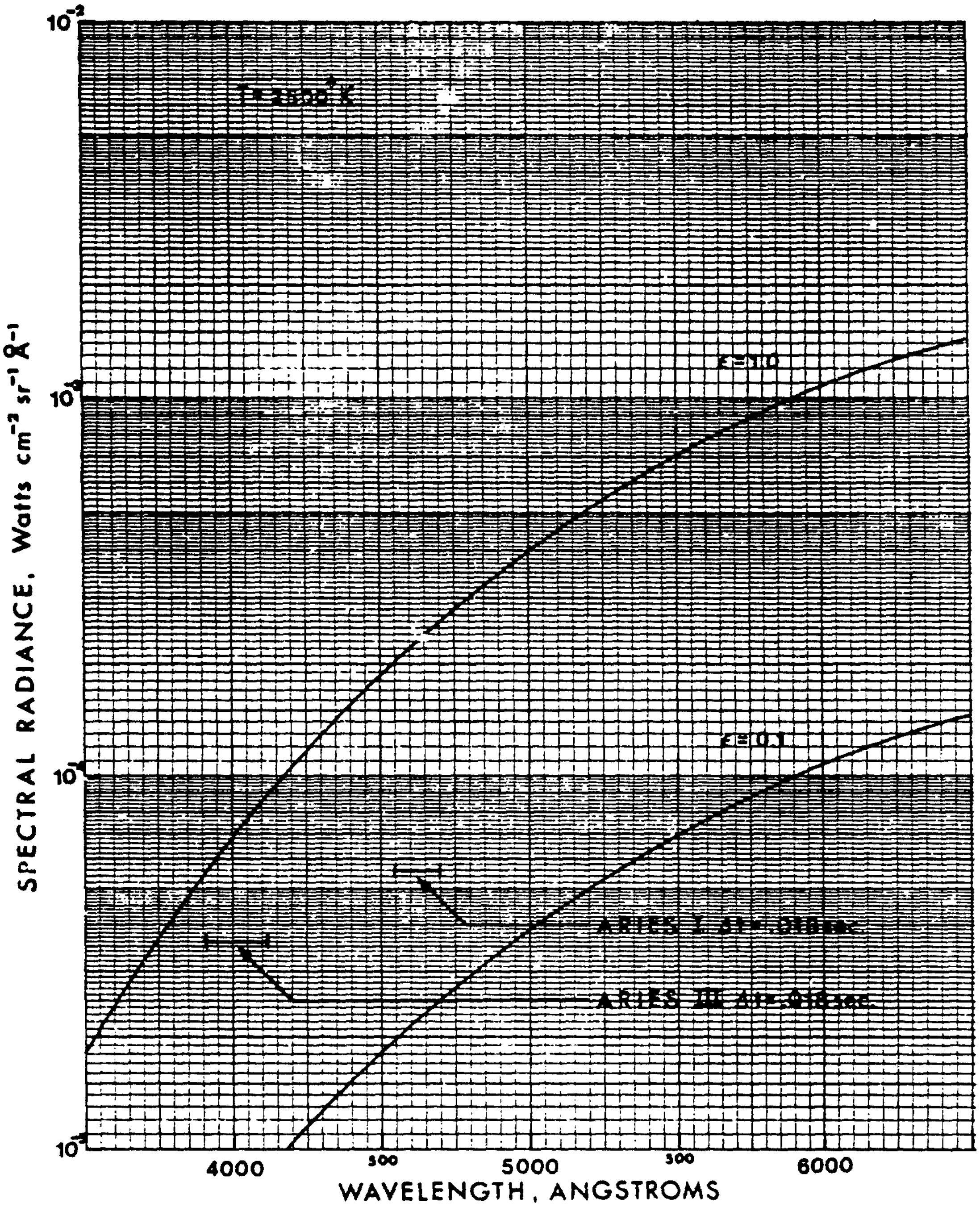


Figure 3. ARIES I and III threshold sensitivity superimposed on black body radiation curves for T = 2500 °K and two values of emissivity.

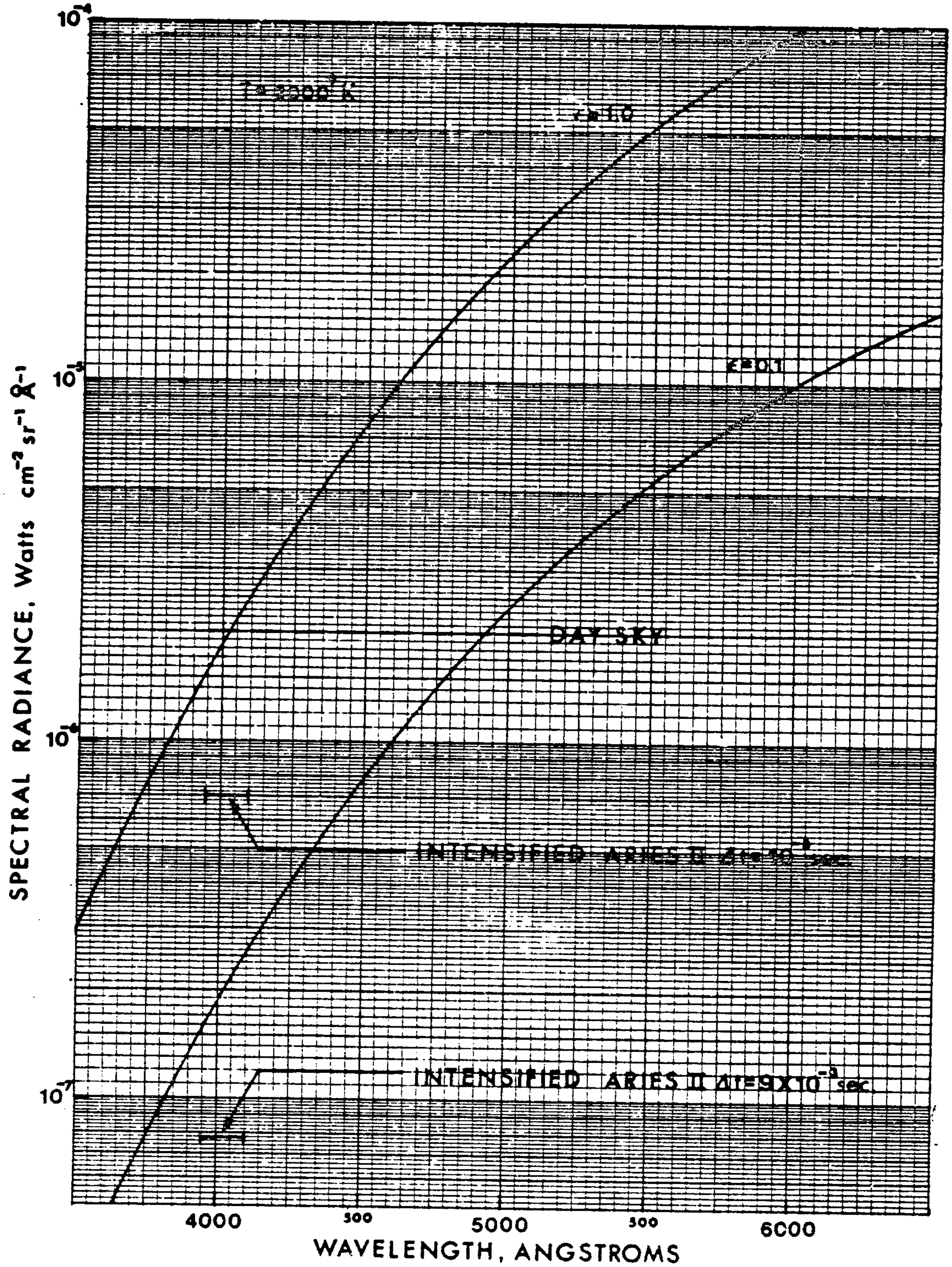


Figure 4. ARIES II (intensified) threshold sensitivity superimposed on black body radiation curves for T = 2000 °K and two values of emissivity.

Each of the three figures shows the black body spectral radiance for a given temperature relevant to the HE detonation, 3500°K, 2500°K, and 2000°K. Curves are shown at each of these temperatures for emissivity values of unity and ϵ = 0.1.

If a source of radiation has unity emissivity, and if that source is of uniform temperature, then by the laws of physics no spectral line radiation can be observed. On the other hand if the source has some degree of transparency the spectral lines will stand out over the continuum radiation (provided also that there is sufficient instrument resolution). This occurs because the emissivity of a spectral line will tend toward the black body limit (ϵ = 1.0), depending upon the number of atoms in the line of sight which are radiating and the inherent strength of the line, while the continuum emissivity must decrease as the transparency increases.

We have no apriori knowledge of what continuum emissivity levels to expect for HE detonations. Undoubtedly the emissivity will vary as a function of time, amount of detonatable material and the position on the fireball which is viewed by the instruments. We do know that experimenters with uncalibrated high-resolution equipment using static exposures (i.e. time-exposures) have observed the spectral lines of metallic species in small HE detonations. Other sources with which we are familiar have a continuum emissivity of about ϵ = 0.3 in the visible spectral region. We shall assume for present purposes that the emissivity of the detonation products of a 50 to 100 lb HE explosion is also in the vicinity of ϵ = 0.3.

Given the above background information we may proceed to predict the possible performance of the three instruments.

Using 25 micron slits and an Eastman-Kodak High Speed Instrumentation Film (Type 4XN) the threshold sensitivities for ARIES I and III spectrographs are estimated to be as indicated in Figure 2. Threshold sensitivity is defined as that level of continuum spectral radiance which will produce a density level of D = 0.1 above the fog level of the film. If the

spectral radiance of the source exceeds the threshold sensitivity a usable data will result.

The threshold sensitivities for ARIES I and III spectrographs as shown in Figure 2 are for an exposure time of 1 millisecond. If the source temperature equals or exceeds 3500 °K for a period of a few milliseconds then these two instruments should produce a usable single frame record of the very early phase of the detonation, provided of course that the shutter is open at the time of detonation.

Figure 3 shows the threshold sensitivities of ARIES I and III instruments for exposure times of 18 milliseconds (i.e. a frame rate of 20 fr/sec and a sector shutter of 130 degrees) superimposed on plots of spectral radiance for a black body source at a temperature of 2500 °K. We note that at this temperature and for an emissivity of around $\epsilon = 0.3$ the ability to record data is marginal. If the source temperature were to drop below 2500 °K the instruments would not record.

In the 1000 °K temperature drop between 3500 °K and 2500 °K the spectral radiance has dropped by a factor of 57 at 4000 Å. In the next 500 °K drop in temperature, to 2000 °K, the spectral radiance decreases by a further factor of 35 at that same wavelength (compare Figures 3 and 4)

Preliminary analyses such as these had led HSS Inc to propose that one of the spectrographs be modified to include an image-intensifier tube which would enhance the sensitivity of that instrument. In the program which finally evolved ARIES II was designated for that purpose. Because ARIES II would view the extreme edge, or just beyond the edge of the fireball, it can expect to see the least amount of radiation. Indeed even if hot fragments pass through its field-of-view their velocity will be such that the exposure time will be very short.

We shall examine the predicted performance for ARIES II in two situations. In the first case let us assume that the line-of-sight of this instrument passes through the edge of the fireball at a time like 50 milliseconds

and that the exposure time is 9 milliseconds (a frame rate of 40 fr/sec). Let us further assume that the fireball temperature is 2000 °K. If the instrument has the sensitivity shown in Figure 4, then it will record at respectable density level on the film.

In the second case we examine the ability of fragments passing through the field of view of the instrument to produce recordable spectra. The distance, d, from the instruments to the detonation point is 4500 ft. The focal length, f, of the objective lens is 500 millimeters and, if we assume a 25 micron slit, the horizontal field-of-view of the spectrograph Δh will be determined by the projection of the slit width Δs back to the source. (Note, slit height determines the field of view in the vertical direction).

$$\Delta h \text{ (ft)} = d\text{(ft)} \frac{\Delta s \text{ (mm)}}{f\text{ (mm)}} \qquad (5)$$

$$\Delta h = 4500 \times (.025/500) \text{ ft}$$

$$\Delta h = 0.23 \text{ ft}$$

If a fragment moving at a velocity of 10,000 ft/sec passes in a horizontal direction through the field of view of the instrument the equivalent exposure time will be 0.23/10,000 or 2.3×10^{-5} sec.

In figure 4 we give the threshold sensitivity for a 1 millisecond exposure as 7×10^{-7} watts cm^{-2} sr^{-1} $\mathring{A}^{-1}$. This sensitivity value would be reduced, in this situation, by the ratio of exposure times (i.e. 1/.023 = 43) to a value of 3.0×10^{-5} watts cm^{-2} sr^{-1} $\mathring{A}^{-1}$.

Now a comparison with the spectral radiance data for a source at 2500 °K (figure 3) indicates that the fragments must have a temperature of at least that amount in order to produce usable spectral data.

A potential problem area is indicated in Figure 4 by the level of the spectral radiance of the day sky (2×10^{-6} watts cm^{-2} sr^{-1} $\mathring{A}^{-1}$ in the green to violet regions of the spectrum). To alleviate this problem, and also maintain the full sensitivity incorporated into the Intensified ARIES II,

the instrument was located with respect to the source such that the background for its field-of-view was a mountain range. Also it was requested that the event be conducted just prior to sunrise. Background spectral radiance was expected to be reduced below a detectable amount by these precautions.

2.3 ARIES I Adaptations.

ARIES I spectrograph did not receive any modifications from its basic configuration other than to shift the wavelength coverage to the spectral region from λ 4576 Å to 4710 Å. Other instrument parameters as employed on Event 1 are given in Appendix A.

In the case of ARIES I the sector shutter was set at its maximem opening (130 °) and a frame rate of 20 fr/sec was used. Under these conditions the probability was 2 to 1 against recording the initial high-temperature phase of the explosion which lasted only a few milliseconds. However, the probability of recording several frames of late time fireball were increased by the choice of exposure time (18 milliseconds).

The ARIES spectrographs employ Aerial lenses as the internal Littrow lens which serves both as collimator and camera lens. Aerial lenses are abberation corrected for the photographic region above a wavelength of 5000 Å. Their use below that wavelength requires a refocusing of the instrument each time the wavelength is shifted. Optimum focusing requires that the spectrum of a reference lamp be photographed each time the grating position is moved an incremental amcunt by a micrometer screw. A study of the resulting record will then permit the proper micrometer setting to be determined. Since the wavelength settings of all three instruments were changed from their original settings refocusing was required in all cases.

ARIES I refocusing was performed with a Xenon lamp. A typical frame with the final focus settings is shown in Figure 5. It is estimated that an image quality of 30 lp/mm was achieved, which would give a spectral resolution of 0.17 Å.

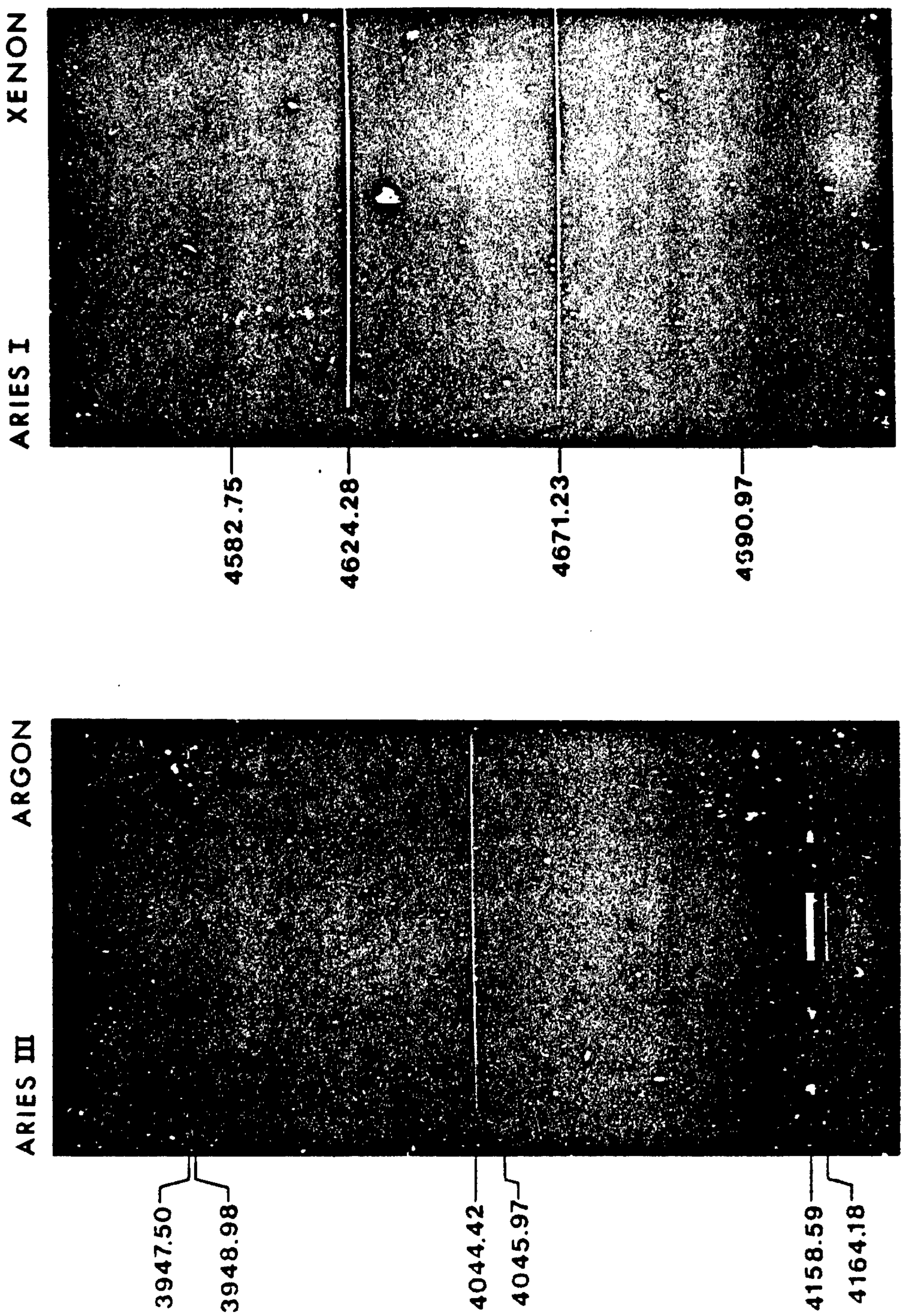


Figure 5. Final focus spectra for ARIES I and ARIES III spectrographs, Event 1. Pictures are X4 enlargements of actual records.

2.4 ARIES III Adaptations.

ARIES III also was operated at a frame rate of 20 fr/sec, giving an exposure time of 18 milliseconds. The sector shutter was removed on this instrument, however, to eliminate the possibility of any dead time between frames. When the shutter is removed, the instrument becomes a framing spectrograph when the film is stationary and a streak spectrograph when the film is in motion during the transport time. Some ambiguity can result due to overlapping of spectra from the different time phases of the explosion; however, that risk was worth the certainty of an exposure during the high-temperature early-phase of the explosion.

Other operating parameters of ARIES III are given in Appendix A. Figure 5 shows a frame of the final focus run of the instrument using an Argon lamp as the source. Image quality was in the vicinity of 30 lp/mm giving a resolution of 0.27 Angstroms.

To appreciate the difference in sensitivity between a camera and a high-resolution spectrograph we shall make a rough comparison between these two types of instruments. A camera which uses panchromatic film would form images employing all the light available in a 2300 Å spectral range from say 3900 Å to 6200 Å. If we assume a continuum source, and a spectral resolution of say 0.23 Å for a high resolution spectrograph, then the relative exposures between the two instruments (neglecting differences in internal transmissions) is 2300/0.23 or 10,000 to 1. It takes a lot of light to record on a high resolution spectrograph in comparison to a camera! One can thus appreciate the necessity to have the best possible f/number, and longest possible exposure times for high-resolution spectrographs.

2.5 ARIES II Adaptations

ARIES II spectrograph underwent a considerable transformation in the process of converting it to an image intensified spectrograph.

An around-the-clock effort was required, beginning on the start date of the contract amendment (31 October 1978) to have the instrument modified, shipped, installed in the field, aligned and focused, and ready for the event on the morning of 15 November 1978.

The method proposed to AFTAC for obtaining a high-resolution image-intensified cine-spectrograph in the least expensive manner was implemented. It was accomplished in the following manner: The image-intensifier and camera sections of a low-resolution, slitless, objective-spectrograph (shown in Figure 6; characteristics are given in Table 2) were removed from their mounting base, remounted on a shorter base frame, and grafted onto ARIES II as shown in Figure 7. Immediately upon completion of the modifications the instrument was shipped to the field. Alignment and focusing were thus performed under difficult and trying circumstances in the cold November nights of the open desert.

The operating parameters of the image-intensified ARIES II spectrograph are given in Appendix A. Contrary to the instrument plan a frame rate of 40 fr/sec was used on ARIES II.

2.6 Field Operations

The three spectrographs and boresight camera were mounted on a eight by eight foot square concrete pad. Two trays were designed to hold the three spectrographs supported by three drill press columns and tables. The two trays had adjustments for precision elevation and azimuth control for precise instrument aiming and alignment. The boresight camera was mounted on a separate drill press column and table. A photograph of the complete set-up is shown in Figure 8. Close-up views of the four instruments are shown in Figures 9 through 11.

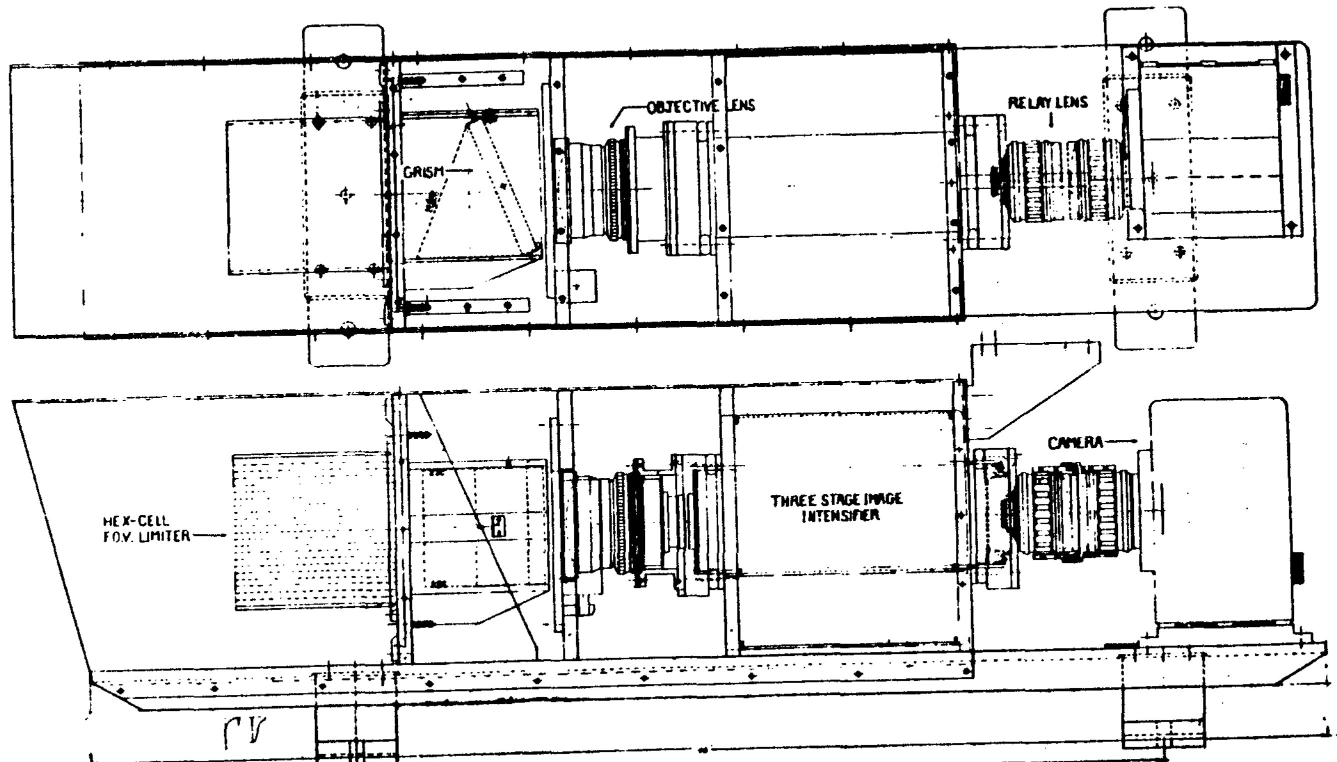


Figure 6. Layout drawing of the Cygnus spectrograph; an image intensified, slitless objective spectrograph used for nighttime artificial auroral spectroscopy.

TABLE 2. Characteristics of the Basic Image-Intensified Cygnus Spectrograph.

SPECTRAL FEATURES	
Wavelength Coverage (nominal)	4200 Å - 8000 Å
Linear Dispersion (nominal)	220 Å/mm
Grating Rulings	600 g/mm
Wavelength Resolution	8 Å
OPTICAL FEATURES	
Configuration	Objective
Objective Lens	Super Farron
(a) f/n	0.86
(b) f.l.	76 mm
Field-of-View	2°
Resolution (Image Tube)	
(a) Center	28 lines/mm
(b) Edge	25 lines/mm
ELECTRONIC FEATURES	
Image Intensifier	VARO 8606 (ABC)
(a) Type (electrostatic)	3-Stage
(b) Cathode Response	S-20VR
(c) Screen, Phosphor	P-11
(d) Radiant Power Gain	40,000
(e) End Plates	Flat, fiberoptic
(f) Power Requirement	6.75 VDC
RECORDING FEATURES	
Camera Type	Flight Research IVC
Film Size	35mm x 100 ft
Format Size	20.4mm x 18.6 mm
Shutter Mode	Open to Open
Shutter Sector Opening	130°
Shutter Program Options	10, 5, 2, 1, .5, .2, .1, .05, fps
Film Type	4XN

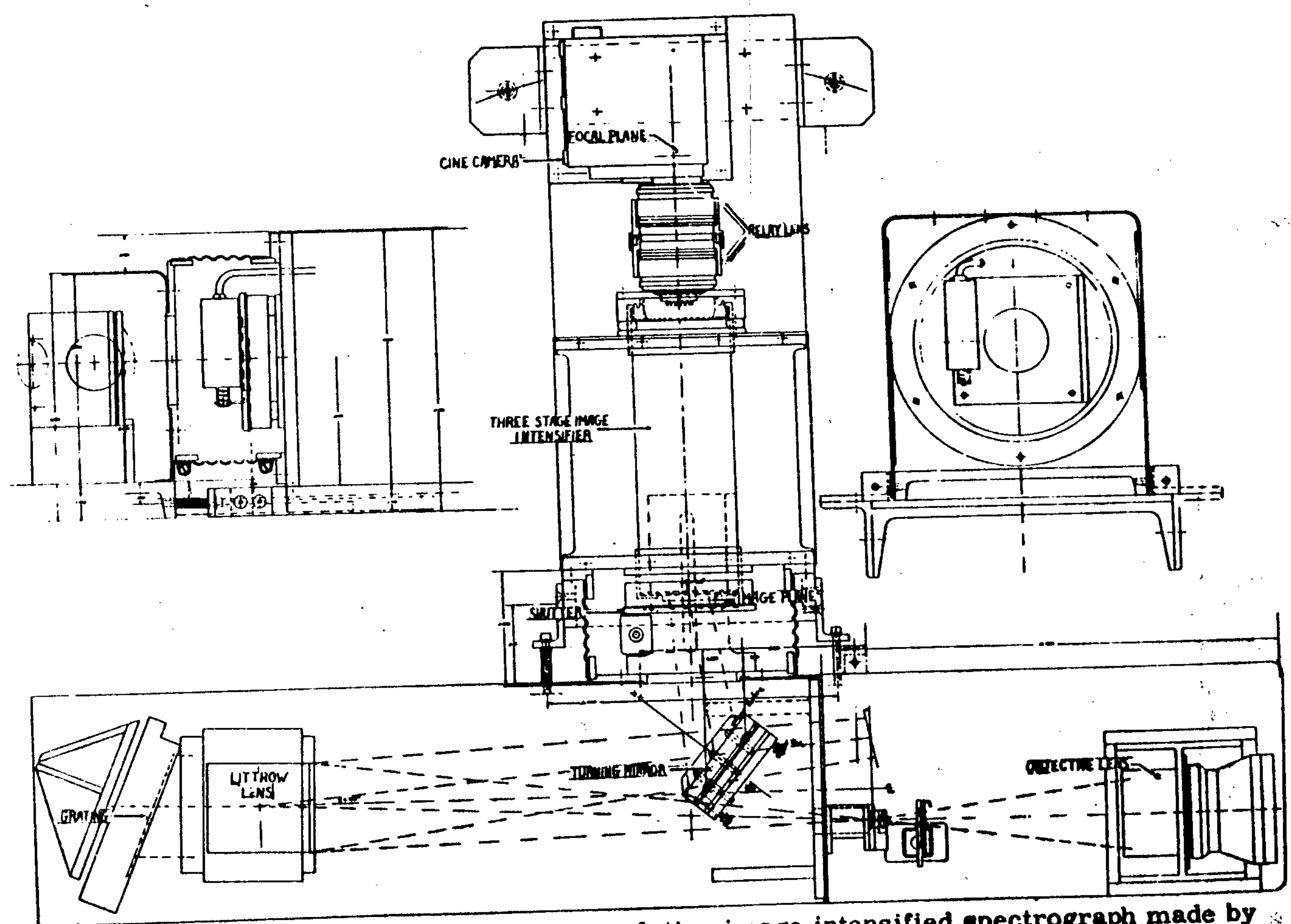


Figure 7. Layout drawing of a high resolution image intensified spectrograph made by grafting sections of the Cygnus spectrograph to ARIES II.

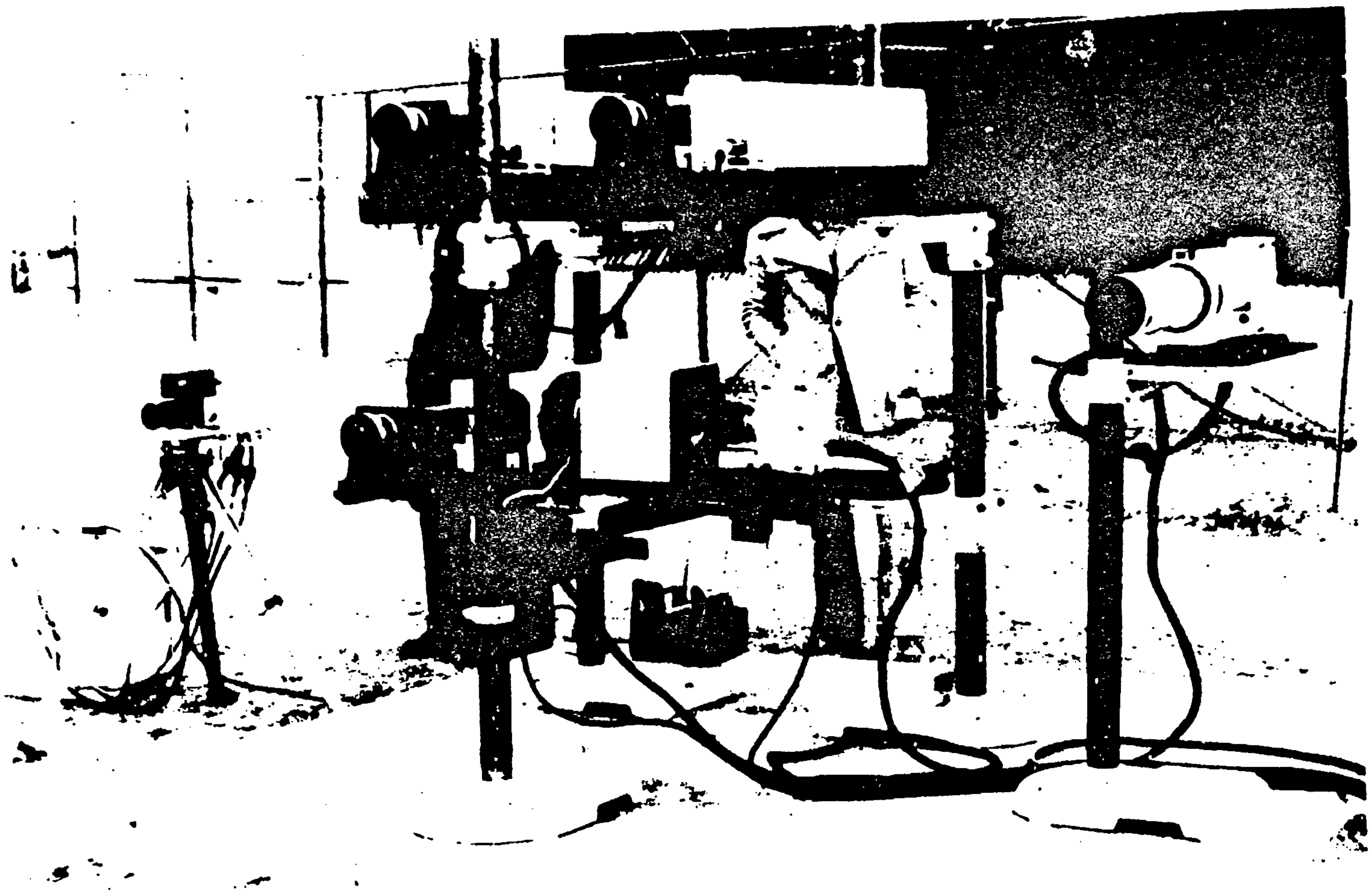


Figure 8. Photograph of the HSS Inc field installation for Event 1. ARIES I and III are on the top platform of the large mount; ARIES II is on the bottom platform, and the boresight camera is to the right on its own pedestal.

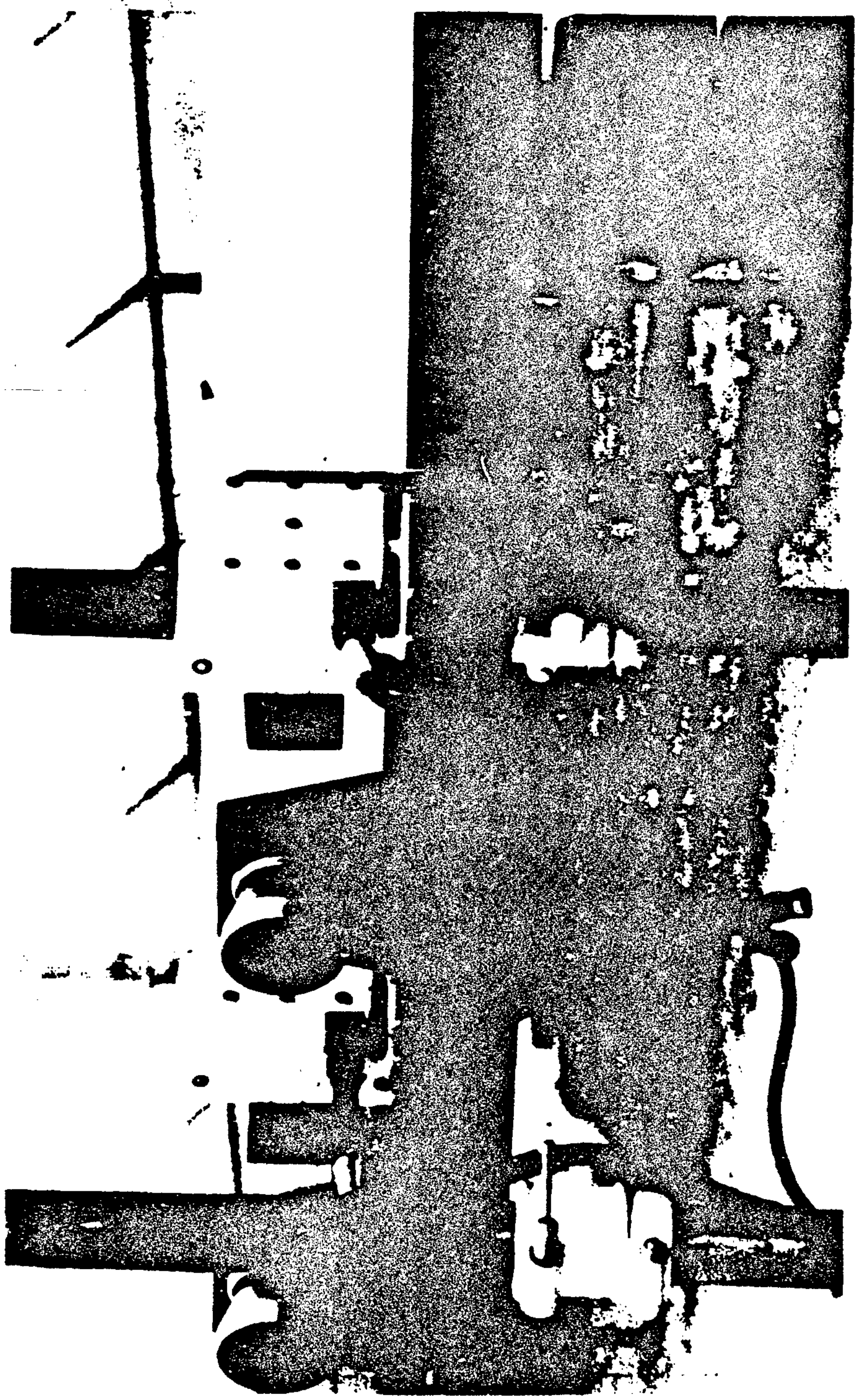


Figure 9. Close-up view of ARIES I and ARIES III spectrographs.

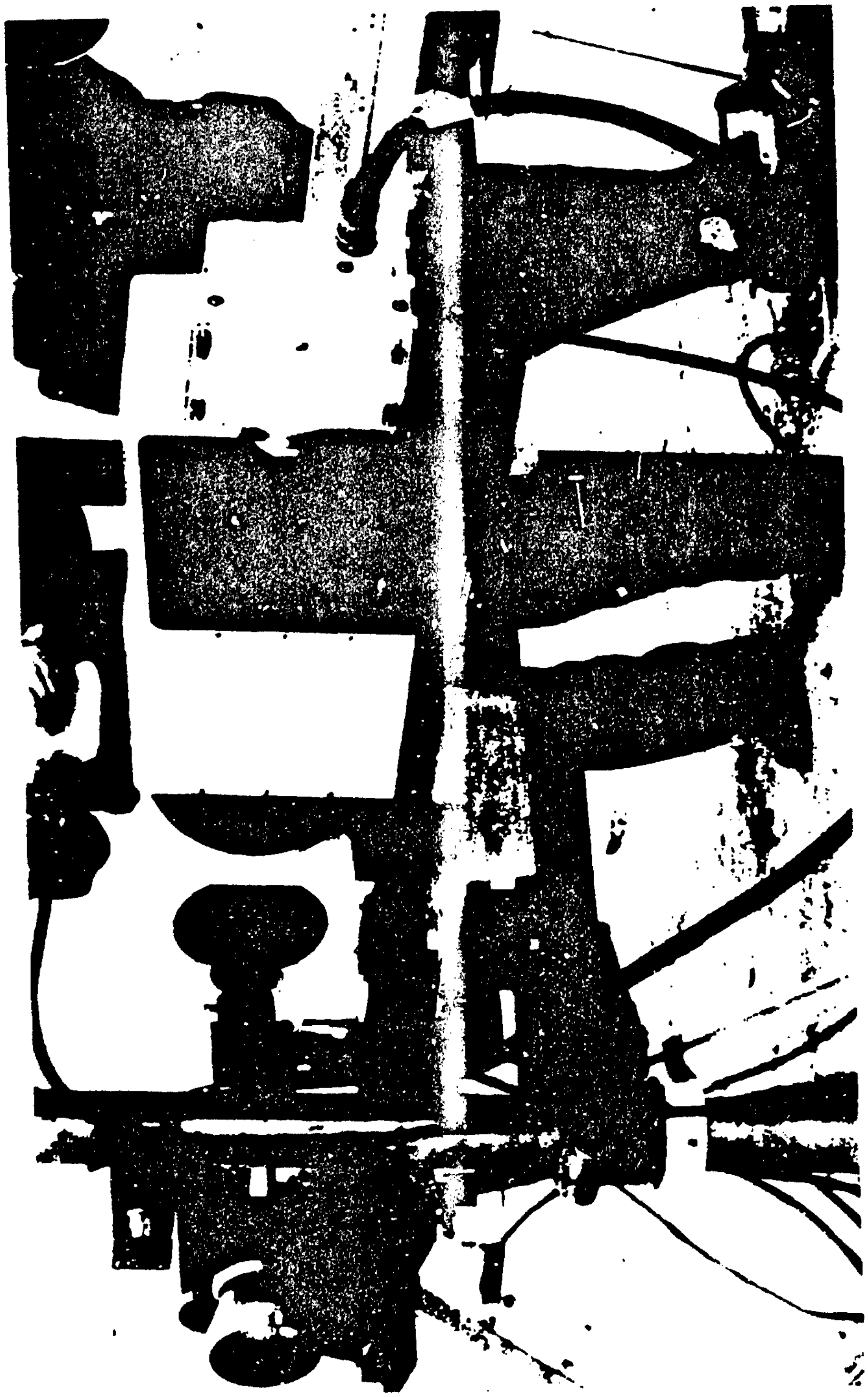


Figure 10. Close-up view of the image-intensified ARIES II spectrograph.

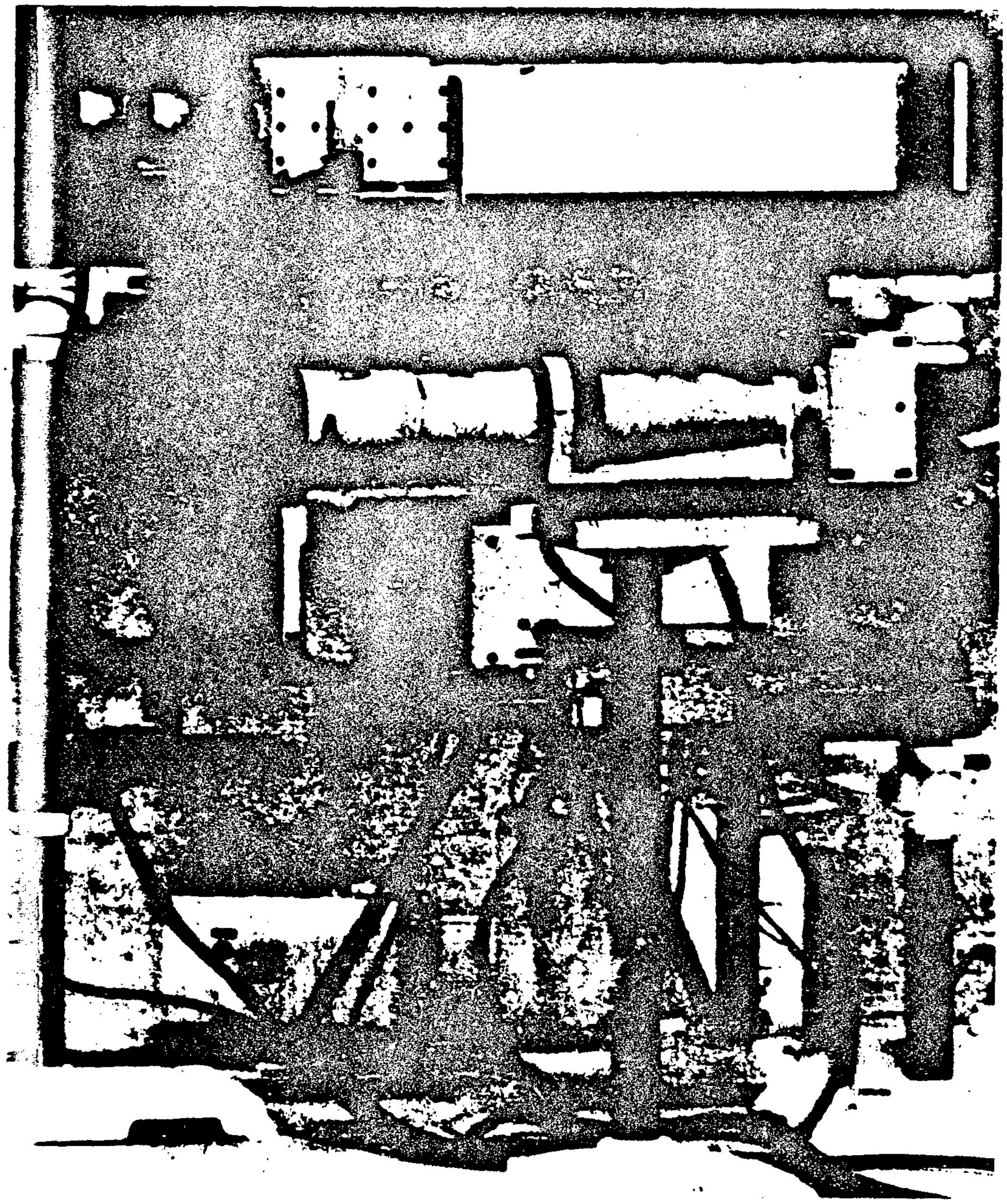


Figure 11. Close-up view of the boresight camera with the spectrographs and mount in background.

3. RESULTS - EVENT 2

3.1 ARIES I and III Spectrographs

ARIES I and ARIES III spectrographs each recorded a single moderately dense image of the fireball. (By convention this frame is designated the zero frame). ARIES I recorded several very weak exposures on successive frames while ARIES III recorded only the single, zero frame, exposure. The fact that ARIES III did not record any weak exposures after the zero frame is undoubtedly due to the fact that the transmission of the lenses used in these instruments is less in the near ultraviolet spectral region where ARIES III operated than the blue spectral region where ARIES I operated. The fireball may also have had less light output in the near ultraviolet spectral region, which would also have contributed to less exposure at the film plane of ARIES III.

On the basis of fireball brightness temperatures vs time measured by Sandia Corp. on previous events, the exposure calculations of HSS Inc indicated that good exposures should be obtained on at least one frame of the ARIES I and III spectrographs (see Reference 1, page16). Consequently it was not unexpected that only a single usable spectrum was obtained by each of these instruments.

The shutter on ARIES III spectrograph had been removed so that no dead-time would occur in its ability to record the fireball spectrum. It would appear that the film was in the stationary position when the detonation occured. There is no image streak when the film was transported to the next frame thus indicating that the fireball temperature is high enough to record on this instrument for a period of only a few milliseconds, again in accordance with predictions based on Sandia Labs brightness temperature time histories for similar devices.

By good fortune the shutter of ARIES I spectrograph was open at zero time, thus enabling the instrument to record the fireball spectrum with a good exposure. ARIES I and III operated at 20 frames per second. ARIES I had a 130° sector shutter (maximum opening) giving 18 milliseconds of recording time and 32 milliseconds of dead-time for each frame. The probability was therefore almost two to one against the shutter being open at zero time.

3.2 ARIES II Spectrograph

ARIES I and III spectrographs were aimed so that the projection of their slits fell on the device. The primary objective of those two instruments was to record the fireball spectrum. ARIES II spectrograph was aimed so that its field-of-view was offset 10 meters from the device. The primary objective of ARIES II spectrograph was to record the spectra of the burning fragments which would pass through its narrow field-of-view. The offset distance of 10 meters was chosen to prevent the fireball from entering the field-of-view at early times.

ARIES II spectrograph was modified for these events by including a three-stage electrostatic image intensifier tube. Predictions had indicated that such intensification was required to record the spectrum of the fragments. The exposure time for the spectrum of the fragments is determined by the time required for a fragment to pass through the narrow field-of-view rather than the interframe time of the recording camera. For a fragment traveling at 2000 m/sec in a direction perpendicular to the slit the exposure time would be 70 microseconds, for example.

ARIES II recorded very, very weak spectra on a half dozen frames. There is evidence that some of these spectra may be from the streamers created by the fragments passing through the field-of-view. The weakness of the exposures makes it extremely difficult to determine if there are any spectral lines superimposed on the continuum spectra.

ARIES II spectrograph was operated at 40 frames per second with a 130° sector shutter giving 9 milliseconds of exposure time and 16 milliseconds of dead-time between frames.

3.3 Boresight Camera

A Flight Research Model IV C 35mm framing camera was operated in conjunction with the three spectrographs. Its primary purpose was to provide a pictorial display of the fireball and fragments from the same station location as the spectrographs. Such pictures have been found on previous occasions to be of assistance in interpreting the geometric aspects of spectrograms recorded by these same spectrographs. All three spectrographs and the boresight camera employed 500 millimeter objective lenses so that their magnifications were identical.

The boresight camera was loaded with XR (Extended Range) film. This film was used for several reasons: (1) It is virtually impossible to over-expose XR film thus one camera can suffice where a battery of cameras using conventional film would be required to capture, without over-exposure, the full brightness range of an explosive phenomenon. (2) to demonstrate to AFTAC the potential usefulness of XR film to their data gathering missions where economy of space prohibits the use of a large number of cameras, and (3) the possibility that XR film might lead to interesting photographic diagnostic information independent of the information gathered by the spectrographs.

The boresight camera recorded an excellent sequence of 50 pictures. One can only wish that a high speed camera were used in order to capture the early phase of the explosion. The zero frame of the boresight camera has been established as having been taken at approximately 20 milliseconds after zero time. Much information of potential diagnostic importance was therefore missed.

Some background information on XR film is important to an interpretation of the pictures obtained with that film. The particular version of the film used on Events 1 and 2 was SO-184 (i.e. an Eastman Kodak Special Order film). It is called Black and White XR film even though its three layers are distinguished by different colors: yellow, magenta (red) and cyan (blue).

The three layers have different ASA ratings as follows:

Layer	Color	ASA Rating
Fast	Yellow	400
Medium	Magenta	10
Slow	Cyan	.004

An important aspect to keep in mind at all times is that the color one sees when viewing an image on XR film has nothing to do to with the colors of the object which was photographed but is strictly related to the brightness of the object. The very brightest objects will appear as blue, the next bright as red and the faintest as yellow.

Color or black and white prints may be made from an XR negative film. Combinations of color filters and print papers with different color sensitivities may be used to emphasize or de-emphasize details within a scene. With XR film one can obtain much information than with a battery of cameras using conventional films. For example, to provide the same information that XR film captures would require that several cameras (with a wide range of exposure settings) be synchronized in their framings, that their magnifications be identical and their images superimposed perfectly frame by frame in a printing process. The printing process would require that the variety of exposures be identified by color coding so that a pile-up of density did not occur. The net result would equate to a color print made from a single XR film.

For further details on XR film characteristics the reader is referred to the description literature presented in Appendix B.

4. DATA REDUCTION

4.1 ARIES III Spectrogram

The single spectrogram recorded by the ARIES III spectrograph is shown in Figure 12. To aid in the identification of emission line features solar spectra were taken after the instruments were returned to HSS Inc. The solar spectra are placed above and below the ARIES III spectrum in Figure 12 for comparison purposes. Spectral lines in the solar spectrum (the Fraunhofer lines) appear in absorption as distinguished from the emission line spectrum of ARIES III.

The spectral lines identified thus far in the ARIES III spectrogram originate from the elements Al, Ti, Mn and Fe. From the nature of the lines observed one can make certain qualitative observations about the characteristics of the source of radiation. The particular spectral lines observed and the energy levels involved in the atomic state transitions are indicated in Table 3.

The first observation is that with the exception of iron all lines observed are so-called resonance lines (i.e. ground state transitions) where the lower energy state is at the zero energy level (or very nearly the zero energy level). Combined with the absence of the multitude of spectral lines of higher excitation energy which one would normally expect to see from steel (i.e. subordinate lines of Fe, Cr, Ti, Mn) the indication is that the source excitation temperature is comparitively low. A further confirmation of this is the absence of the H & K resonance lines of ionized calcium, Ca II, at wavelengths 3933.66 Å and 3968.47 Å which invariably appear in nearly any source of light since calcium is ubiquitous. The first ionization potential of calcium is at 6.11 electron volts.

That the Fe I line at 4045.82 Å is observed indicates a large abundance of iron in the source. This line has a lower excitation potential of 1.48 electron volts. It is inherently the strongest iron line within the spectral range covered by ARIES III nevertheless its presence at low temperatures implies a large abundance of that element.

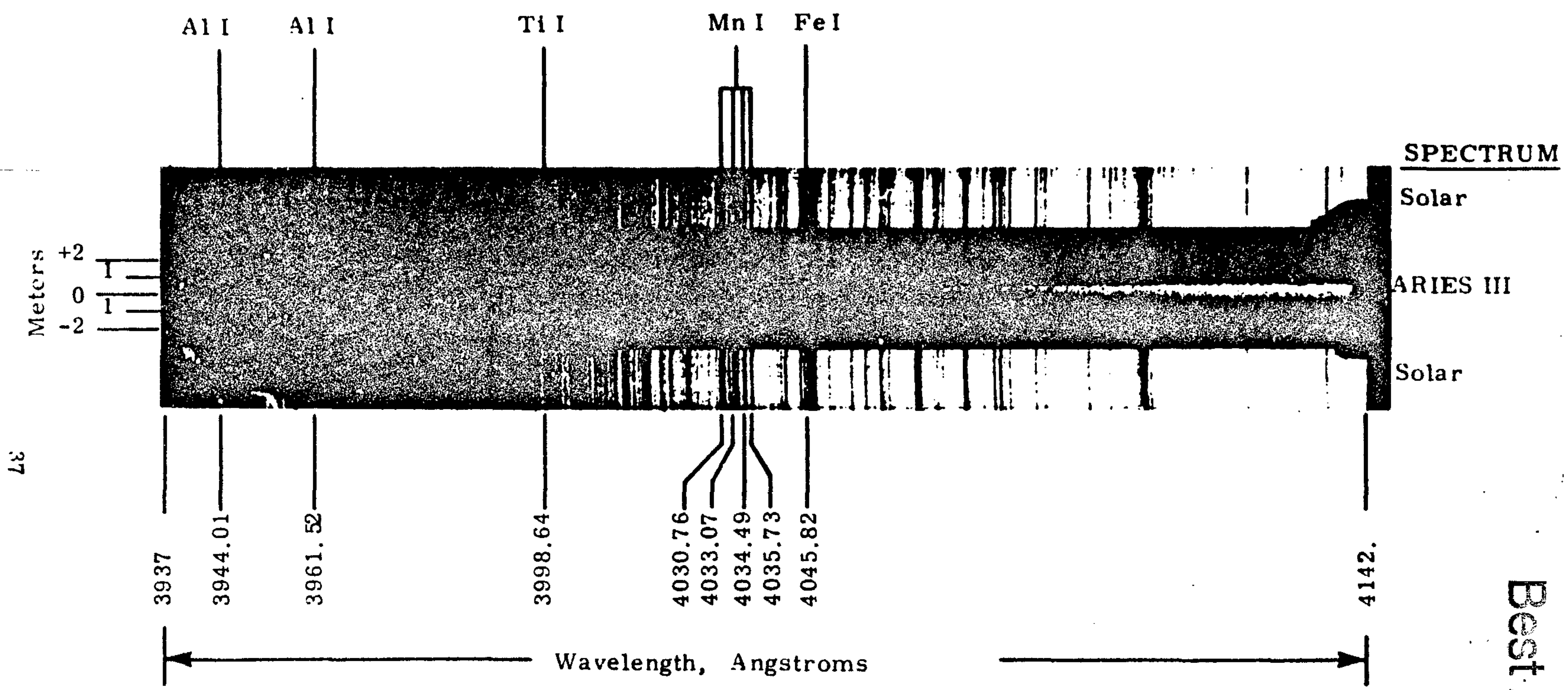


Figure 12. ARIES III spectrum of HE Event (Frame 0) with Solar Comparison Spectrum.

Table 3. Spectral Lines and Excitation Potentials of the Atomic Species Observed in the ARIES III Spectrogram

Element	Wavelength (Å)	Energy Levels Lower (ev)	Energy Levels Upper (ev)
Al I	3944.01	0.00	3.13
	3961.52	0.01	3.13
Ti I	3998.64	0.05	3.13
Mn I	4030.76	0.00	3.06
	4033.07	0.00	3.06
	4034.49	0.00	3.06
Fe I	4045.82	1.48	4.53

All lines observed in the ARIES III spectrogram are inherently the strongest lines of those elements within the spectral range covered by that instrument. They appear broad and diffuse for several possible reasons: (1) they are resonance lines which normally tend to be broad, (2) the element giving rise to the line is present in abundance or (3) a combination of both prior reasons. In the case of Event 2 we would speculate, in the absence of any quantitative analysis, that the third reason is most likely; i.e., that Al, Ti and Mn are present in moderate abundance.

The fireball temperature was sufficiently hot to record on the ARIES III spectrograph for only a few milliseconds as can be gauged from the vertical dimension of the continuum spectrum. The continuum exhibits a bright region approximately one meter in extent in the downward direction of the fireball with another weaker region extending for one meter in the upward direction (the same characteristics are observed in the ARIES I spectrum).

The ability to record the atomic spectra of the fireball for a longer period of time would be dependent upon the source characteristics at later times (temperature sufficient to excite low energy levels) and increased instrument sensitivity (factors which enter into sensitivity are f/number dispersion, film sensitivity, and possible electronic image intensification).

4.2 ARIES I Spectrogram

Only two emission features have been conclusively identified thus far in the ARIES I zero frame spectrogram, Figure 13. These are a single line of Cr I at 4646.17 Å and a very strong molecular band of Al O. A comparison solar spectrum is included in the Figure for reference purposes. Al O is not present in the solar spectrum. The bracket in the figure refers to the region occupied by the Al O band in the ARIES I spectrum. The band head

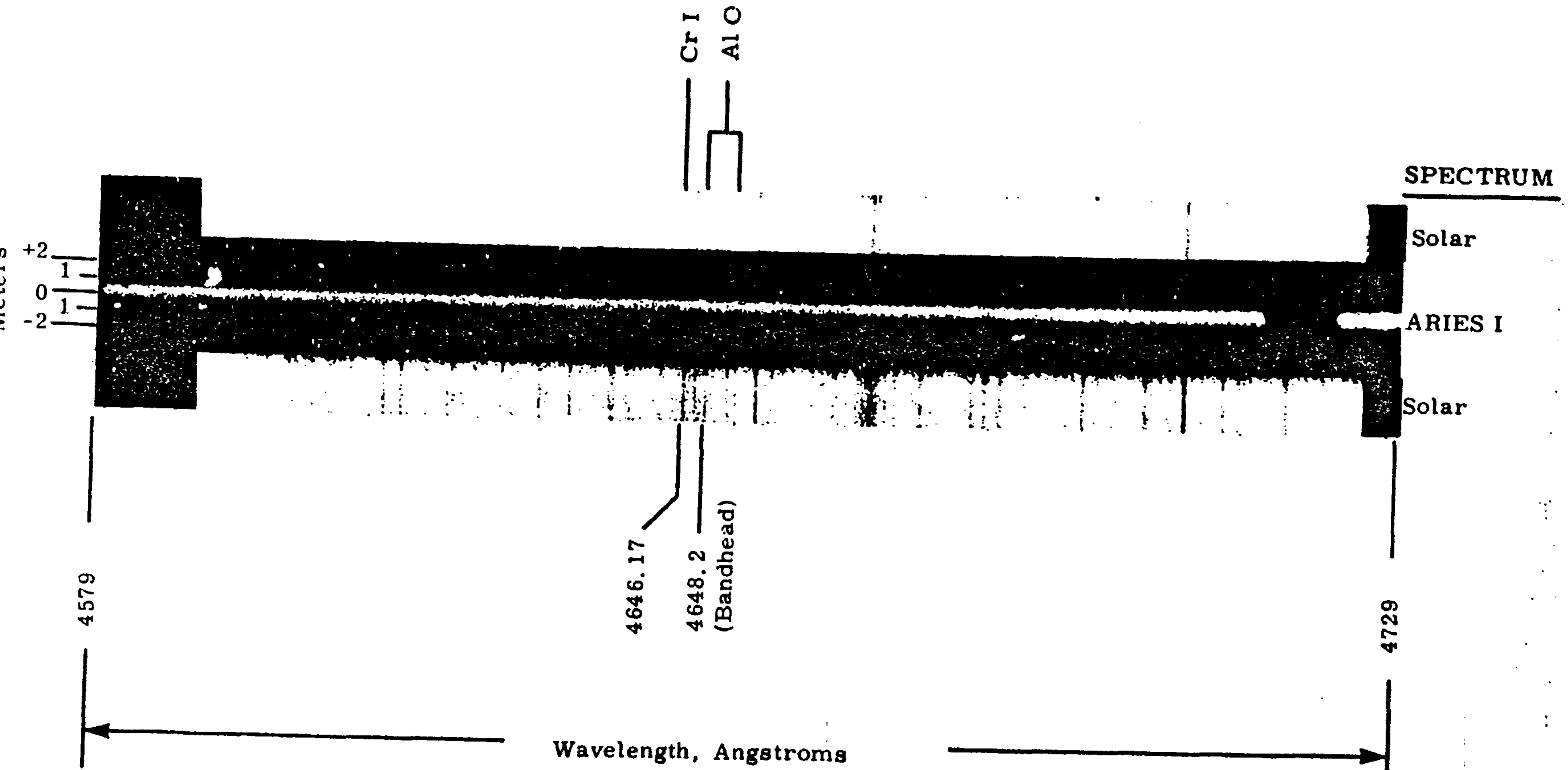


Figure 13. ARIES I Spectrum of H. E. Event (Frame 0) with Solar Comparison Spectrum

of the AlO band which was observed, the (1,0) vibrational transition is located at 4648.2Å; the band is degraded to the red.

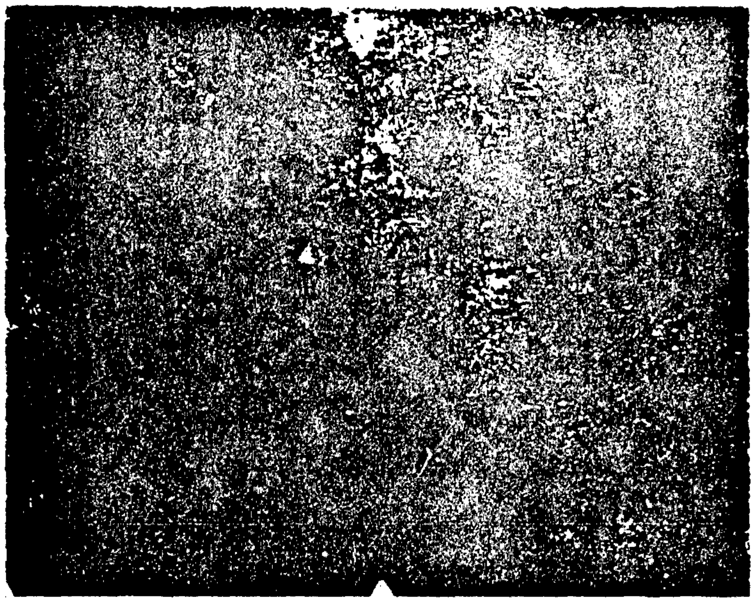
As in the case of the ARIES III spectrogram the two features observed in the ARIES I spectrogram are inherently the strongest features of Cr I and AlO present in the spectral range covered by the ARIES I instrument on this event.

4.3 Boresight Camera

Polaroid color prints of frames 0, 1, 2 and 10 of the boresight camera XR film record are shown in Figure 14. Color prints, because they lack the latitude, do not capture the full dynamic range of color present in the negative XR images, but they are satisfactory for demonstrating the capabilities of that film.

The pictures in Figure 14 are approximately 4X enlargements from the original record. Frame zero demonstrates to some extent the dynamic range of XR film. The faint background and skylight recorded on the most sensitive (yellow) layer of the film. Most of the fireball and streamers recorded on the magenta (red) layer, but at various points on the fireball hot spots were recorded on the cyan (blue) layer.

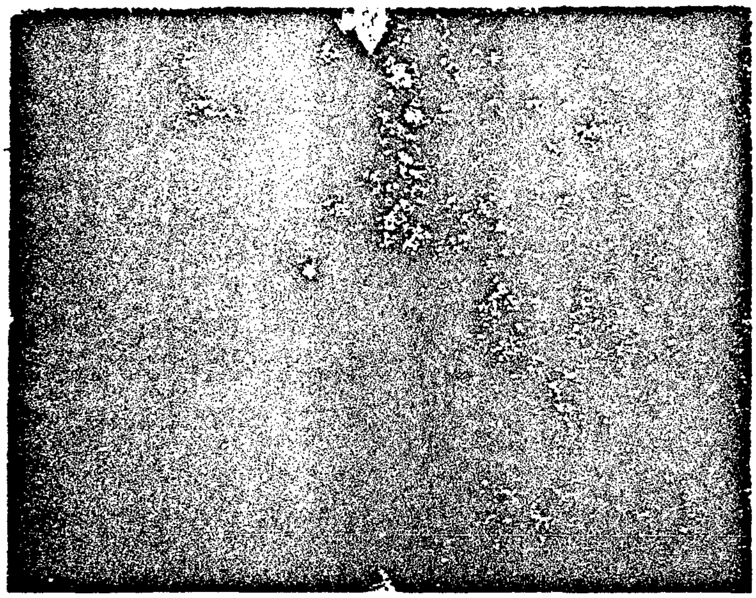
Isolated streamer lengths were used to deduce fragment velocities in Frame 0. Apparent streamer length is created by the comparatively long exposure time (9 milliseconds) and the high velocity of the initial fragments. Streamers of the longest lengths were assumed to be traveling in a direction perpendicular to the line of sight. Velocities of the fragments creating these streamers were determined to be in the vicinity of 1400 meters/sec at the time the picture was taken. Measuring the furthest distance that the fragments had reached and extrapolating backward in time led to the conclusion that the zero frame was recorded at approximately 20 milliseconds after zero time (with a small allowance for slowing down of the fragments).



FRAME 0 20 msec

FRAME 1 45 msec

Figure 14. Boresight Camera Pictures; XR Film, Polaroid Color Prints; Frames 0 and 1.



FRAME 2 70 msec.

FRAME 10 270 msec

Figure 14A. Boresight Camera Pictures; XR Film, Polaroid Color Prints; Frames 2 and 10.

Frame 1 and to a lesser extent frame 2 of the boresight camera record show an "exploded view" configuration (in the blue layer) of debris remnants which appear to have maintained the pre-detonation geometry of some part or parts of the device. Various printing techniques were used to enhance this phenomenon as will be described later.

By frame 10 of the record (270 milliseconds) the fragments emanating from the fireball were of much slower velocity. Very little motion blurring is evident in the trajectory of these late time fragments.

The streamers created by fragments of the device were recorded in the red and yellow layers of the XR film. In the early frames, because of their high velocities the photographic exposure of the streamers is not the 9 millisecond exposure of the camera. Rather it is the time it takes for the object producing the exposure to move a distance equal to its own size. In this case the object producing the exposure appears to be a ball of glowing gas surrounding the fragment. A rough estimate of the exposure time of the streamers in frame zero is one-hundredth the frame exposure time or 90 microsenonds.

The brightest of the streamers have a width of about 10 inches. The profile of the streamer brightness (i.e. brightness distribution at right angles to the direction of travel) has a bell-shaped distribution with half peak brightness like five or six inches.

Observations under a microscope show that many of the streamers have a bright line imbedded within the glowing gas. The width of the line is slightly over an inch in size. The line is not perfectly straight but has a slight sinusoidal oscillation to it. This behavior could be explained if the bright line were due to a burning spot on the fragment and the fragment was tumbling as it sped through the air. Another

explanation, assuming the entire fragment is burning, is that the fragment has a corkscrew trajectory due to its aerodynamic characteristics. The streamer which demonstrates this behavior most beautifully in the original negative and under a microscope is indicated by an arrow in Figure 14 . The Polaroid print of course cannot reproduce the detail present in the original negative.

All the geometric observations made to date on the streamers have been made with measuring eyepieces and a microscope. More quantitative work could be performed with a microdensitometer if the need arose.

The fact that a burning fragment (or a burning spot on the fragment) can be observed within a streamer leads to the definite conclusion that the streamers are optically thin (i.e. partially transparent). It is therefore highly probable that the glowing gas which surrounds the fragment has a discrete emission spectrum. The spectrum could be either the spectrum of shocked air or atomic species vaporized from the burning fragments or a combination of both these possibilities.

Brightness temperatures of the brightest streamers have been estimated from the photographs (see the section on conclusions) but when a gas is optically thin there is little correlation between brightness temperature and either excitation temperature on kinetic temperature. These latter temperatures can be higher, further aiding in the excitation of discrete spectral lines or molecular bands. If the glow present in the streamer is due to gases in non-thermal equilibrium (i.e. not characterized by a temperature) then the spectra must certainly have discrete line features.

A limited attempt was made to find possible correlations among the streamer parameters. Attempts were made to correlate brightness with widths of the streamers, also to discern whether there were different classes of streamer brightnesses. The objective of this search was to see if streamers due to different materials (e.g. aluminum vs uranium) might exhibit different

streamer characteristics. No obvious correlations were found. That is not to say that there may well be correlations, but a much more systematic and quantitative effort would have to be conducted if the correlations are to be found.

It is interesting to speculate what might have been observed with the boresight camera and XR film had its shutter been open at zero time. Undoubtedly the fireball would have recorded dominantly in the blue layer for a diameter of a couple of meters (commensurate with the ARIES I and III spectrogram dimensions). Regions of the fireball beyond the first couple of meters would have recorded dominantly in the red layer. Structural information about the device may well be contained in the very early behavior of the fragments.

The same sequence of pictures from the boresight camera record have been repeated in Figure 15 using black and white print paper. In this instance Kodak Polycontrast Rapid IIC print paper was used. This paper is predominantly blue sensitive with a slight green sensitivity which explains the features which are emphasized in the prints.

One must remember that anywhere that the film has recorded in the red layer the film is overexposed (saturated) in the yellow layer so that a heavy yellow filter underlies the red color. Analogously, anywhere the film recorded in the blue layer the yellow layer is saturated and the red layer may be almost saturated.

In the region of the sky which is pale yellow on the negative film sufficient green light passes through the negative to blacken the print paper. Some green light gets through the red streamers so that they are recorded gray in tone. In the region of the fireball, where a heavy exposure was received on the red layer and some exposure on the blue layer, very little green light gets through in the printing process thus leaving the white image of the fireball.

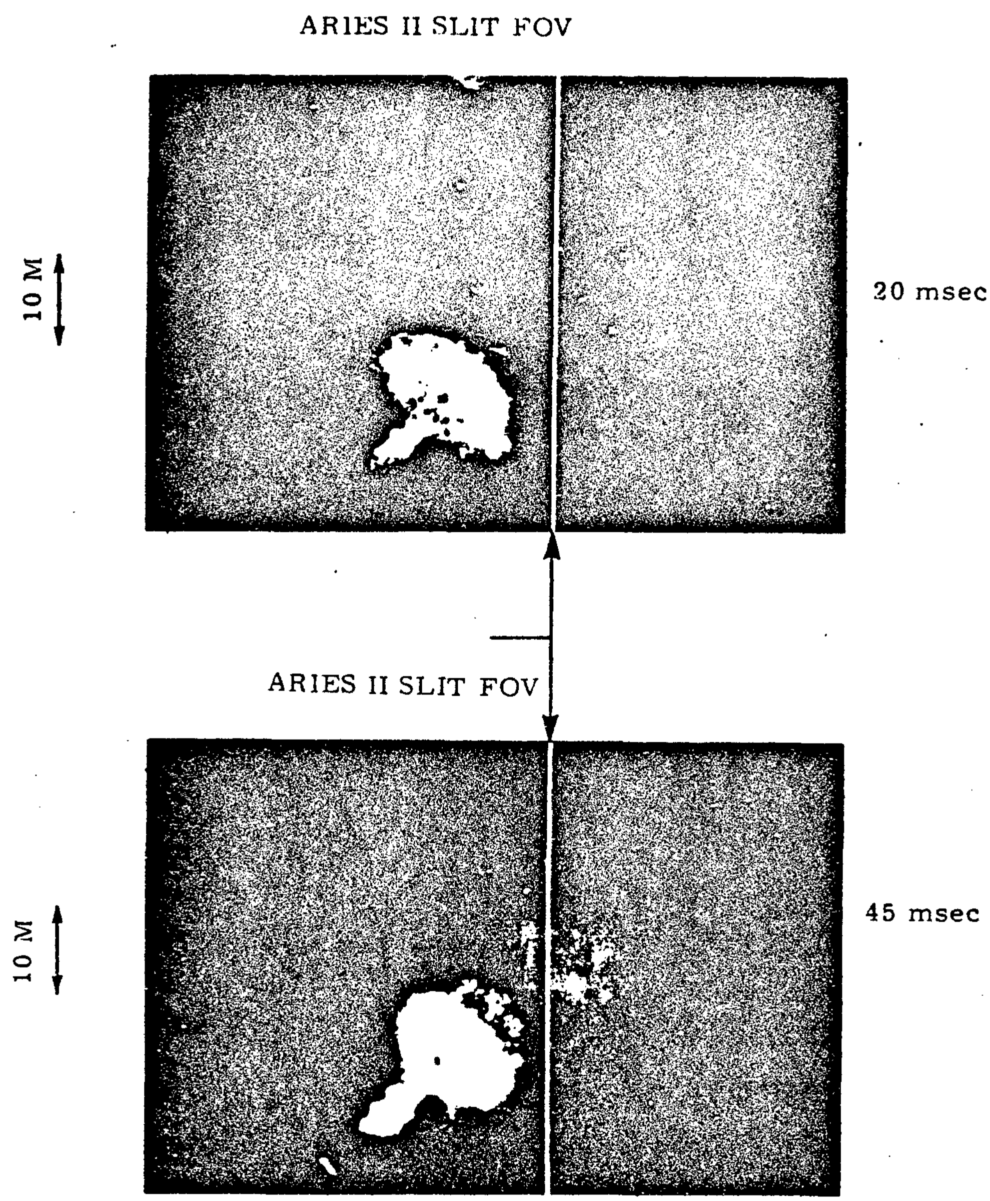


Figure 15. Boresight Camera Pictures; XR Film, Frames 0 and 1. Printed on Kodak Polycontrast Rapid II RC-N Paper.

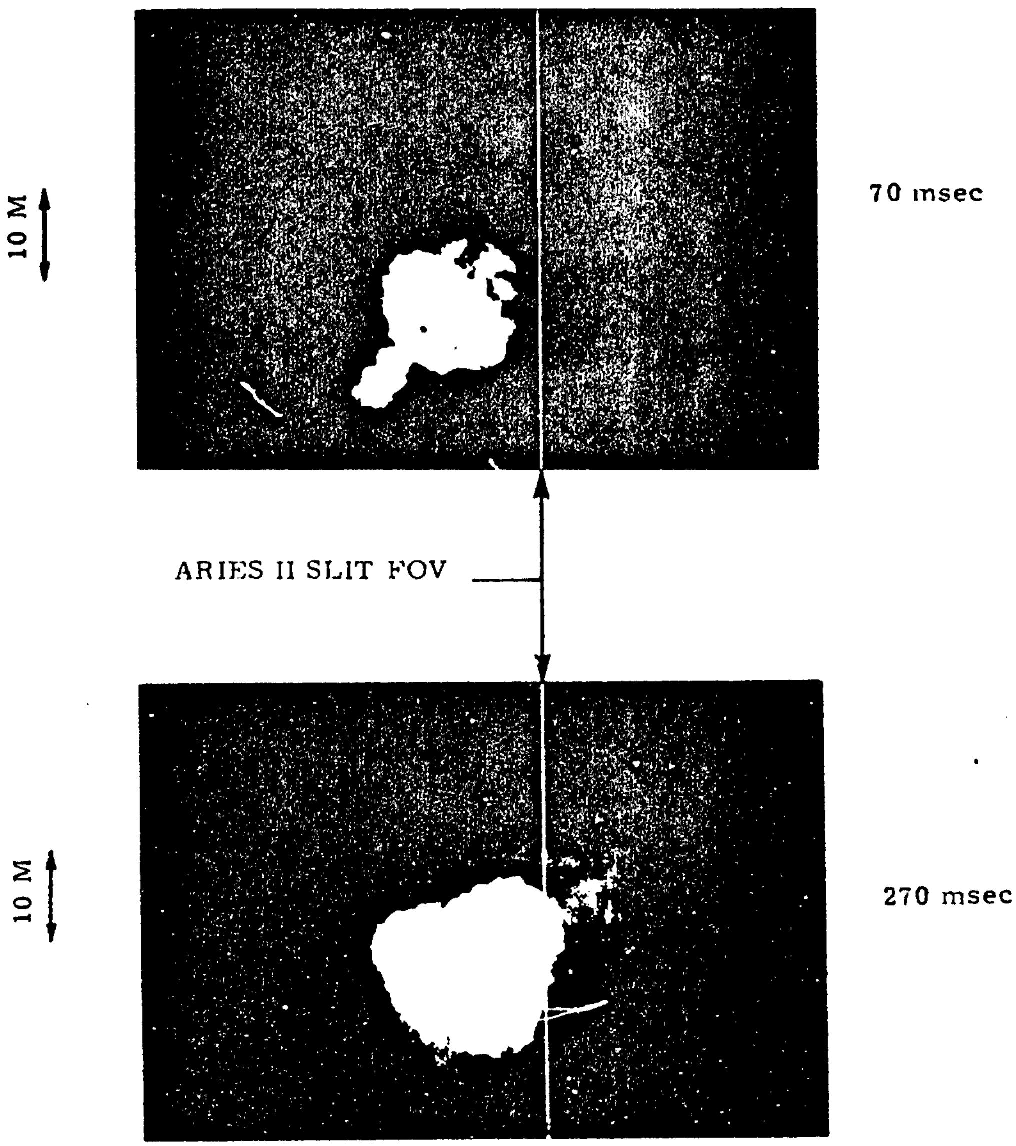


Figure 15A. Boresight Camera Pictures; XR Film, Printed on Kodak Polycontrast Rapid II RC-X Paper; Frames 2 and 10.

Figure 16 is an 8X enlargement of frame 1 of the boresight camera record. Various combinations of color filters and print papers were used in attempts to emphasize the debris structure in the fireball which was observed in the Polaroid color prints. Best results were obtained with no filter using Kodak Panalure paper and a special high contrast developer similar to Formula D-8 (hydroquinone and sodium hydroxide and sodium sulphite). Panalure paper is panchromatic, i.e. it is sensitive to red, green and blue radiation.

The author is only vaguely aware of the configuration and composition of the device which was exploded so that it must be left to AFTAC and Sandia Labs personnel to decide whether any significant information may be determined about the shape of the original device from this picture.

Again we may speculate that more information related to device configuration may be obtained using XR film in a high speed camera. A high speed camera is required to assure capturing the very early phases of the explosion.

4.4 ARIES II Spectrograph

Figure 15 illustrates the position of the ARIES II entrance slit when projected back to the object plane containing the fireball. The projected slit lies 10 meters to the right of the point where the device was detonated. The fireball does not enter the field-of-view of the instrument as was anticipated by pre-event predictions by Maj. Allen of AFTAC and the author.

ARIES II spectrograph operated at the same frame rate as the boresight camera but the framing of the two instruments was independent (i.e. not synchronized). Thus we lack any knowledge of when the zero frame of ARIES II was recorded with respect to zero time of the detonation.

Figure 16. Enlargement of frame 1 from the boresight camera XR film record using contrast enhancement techniques.

It would appear from a study of frames 0 and 1 of the boresight camera that there was every likelyhood of the framing of ARIES II spectrograph being such that very few large fragments passed through the field-of-view during the first two frames. In later frames (e.g. frame 2) there are hardly any bright fragments in the vicinity of the projected slit.

Extremely faint continuum spectra appear on the ARIES II record giving some indication that some luminous substance did pass through the field-of-view. However, the light may be fireball light entering the field-of-view at late times and not streamer radiation.

Attempts to enhance the ARIES II images by printing on high contrast print paper were not successful. Better results were obtained by enlarging onto high contrast negative film. The images were still too faint to ascertain whether any emission lines are contained in the continuua spectra.

Consideration was given to enhancing the images in the ARIES II record by rehalogenation of the original film. Rehalogenation is a procedure whereby the silver image of a processed film is recombined into a soluble silver salt. The new latent image is then developed in a color-plus-dye image. The color-coupler forms a dye image in the immediate vicinity of the reduced silver image. The amount of dye in the image is proportional to the amount of silver reduced. The presence of the dye represents an amplification of the weak image originally present in the film. The process can be repeated through several cycles possibly resulting in a large gain in the effective sensitivity of the film.

Before rehalogenation was attempted the conclusion was reached that the images on the ARIES II record were in all probability due to fireball light; hence the rehalogenation idea was abandoned.

5. CONCLUSIONS

Only a qualitative analysis of the records obtained on Event 2 has been performed. Conclusions drawn from these analysis are as follows:

From the continuum exposures on the zero frames of ARIES I and ARIES III spectrographs, we estimate the brightness temperature of the very early time fireball to be in the vicinity of 3200°K to 3300°K. From a knowledge of the energy levels of the atomic transitions involved in the spectral lines which were observed, we would assume the excitation temperature is somewhere in this same vicinity. True fireball temperature, if a true kinetic temperature exists, would be slightly higher than the brightness temperature.

The low brightness temperatures were not unexpected, because of the Sandia Lab's previous measurements. What is somewhat surprising is that the excitation temperature is also low. Excitation temperature and true temperature are analogous if the fireball is in thermal equilibrium.

Crude estimates of the fireball brightness temperature at later times were made from the exposures recorded on the boresight camera XR film record. It would appear that during the time from 45 to 100 milliseconds the fireball brightness temperature was in the range from 2100°K to 2300°K.

From frame zero of the boresight camera record (at 20 milliseconds) we have estimated, in a similarly crude manner, that the brightest of the fragment trails can be represented by brightness temperatures of around 2600°K. The latter determination is based on the assumption that the glowing region surrounding the burning fragments is localized; i.e., the trail does not persist after the particle has passed--the nature of the trails

in the XR film record gives every indication of this being the case.

The attention to temperature, especially excitation temperature, is important because that parameter is probably the most critical factor in determining which spectral lines and which atomic elements may be observed in the spectra of the fireball and fragment trails. The temperature estimates given above are crude estimates based on the published values of film sensitivities and visual estimates of film densities.

ARIES I and III spectrographs can be radiometrically calibrated so that more precise temperatures can be established. Brightness temperatures can be obtained from the continuum spectra. Excitation temperatures can be obtained from the spectral line intensities.

Preliminary conclusions can be formulated concerning the ability to diagnose materials composition in an HE explosion by use of spectroscopic techniqess. At the outset of the program we had ruled out the possibility of detecting certain elements on the basis of past experience and the excitation energy required to produce their atomic spectra. The elements eliminated at the outset were two of the principal ingredients of plastics (i.e. hydrogen and carbon) and the noble gas elements helium and neon.

A list of eighteen other elements of interest to AFTAC was furnished to HSS Inc. Consultations between Major Allen of AFTAC and D. Hansen of HSS Inc led to the selection of wavelength ranges for the three spectrographs based on the instrument limitations and the desire to encompass the strongest lines of the most important elements of interest.

Of the eighteen elements of interest only five have been identified as being present in the spectra. In Table 4 we review the reasons, in light of the results thus far, why the remaining elements were not observed. We also point out where an expanded wavelength coverage will aid in the

Table 4. Comments on the Observation of Specific Atomic Elements in HE Fireballs

(Based on a Preliminary Analysis of Event 2 Data)

CATEGORY I   Elements unlikely to be observed in an HE Event

Element	Symbol	Reason
Beryllium	Be	High Excitation Energy Required
Cadmium	Cd	High Excitation Energy Required
Zinc	Zn	High Excitation Energy Required

CATEGORY II   Elements with strong atomic lines in the spectral regions covered by ARIES I and ARIES III on Event 2

Element	Symbol	Observed	Reason Not Observed
Aluminum	Al	Yes	------
Lead	Pb	No	Abundance too low
Manganese	Mn	Yes	------
Titanium	Ti	Yes	------
Ytterbium	Yb	No	Abundance too low

CATEGORY III   Elements with strongest atomic lines outside the spectral regions covered by ARIES I and ARIES III on Event 2

Element	Symbol	Observed	Improvement with Wider Coverage
Chromium	Cr	Yes	More sensitivity to lower abundance
Copper	Cu	No	Improved detection capability
Gadolinium	Gd	No	Improved detection capability
Iron	Fe	Yes	More sensitivity to lower abundance
Lanthanum	La	No	Improved detection capability
Lithium	Li	No	Detection at very low abundance
Magnesium	Mg	No	Improved detection capability
Tungsten	W	No	Improved detection capability
Uranium	U	No	Improved detection capability
Zirconium	Zr	No	Improved detection capability

detection of other elements or improve the measurement capability for some of those elements which were detected.

The conclusions presented in Table 4 are tentative being based on the preliminary findings to date. The most important new consideration which has been added beyond the pre-event considerations is the low fireball excitation temperature which was manifested in Event 2. Also the Table pertains only to the fireball and not the spectra of streamers and fragments. The latter must be treated separately.

Appendix C is a listing of the strongest atomic lines of each of the eighteen elements of interest. To determine which elements are likely to be detected and which atomic lines of those elements are the most important in the detection process requires that we have an appreciation of the physical parameters which govern the intensity of a spectral line.

An appreciation of the parameters entering into spectral line intensities may be obtained from Appendix D which describes how excitation temperature is measured for an optically thin source. From Equation D. 6 of Appendix D we see that the integrated line intensity (i.e. the total radiant power under the profile of the line is given by

$$N_{\ell} = \frac{1.054\,(gf)\,n_o L\, e^{-E_{02}/kT}}{\lambda^3\, U} \qquad (6)$$

where:

gf = the weighted oscillator strength

λ = wavelength of the line

$n_o L$ = column density of the emitting atoms (n_o is the concentration atoms cm^{-3} and L is the path length, in cm, through the emitting gas)

E_{02} = upper energy level of the atomic transition giving rise to the spectral line

kT = Kinetic temperature of the gas

U = partition function of the atomic species

From Equation (6) we see that there are four primary factors which will determine the intensity of a spectral line. (We neglect the wavelength factor λ^3 since it will not vary greatly over any wavelength range of interest to the program). These four factors are: (1) the weighted oscillator strengths gf (i.e. the inherent intensities of the spectral lines), (2) the partition function U of the atom, in this case the neutral atom, (i.e. the total number of possible energy states that the neutral atom may find itself in when excited), (3) the column density $n_o L$ (i.e. the total number of atoms per square centimeter in the line of sight of the instrument) and (4) the Boltzman factor exp $(-E_{02}/kT)$.

The spectral lines of interest to this program will have gf values in the range of 0.1 to 1.0. Indeed, in some cases nature is kind and we may find gf values which exceed gf = 1.0.

Elements which have very few spectral lines have small partition functions thus enhancing the intensity of the lines. Elements which have large numbers of spectral lines have large partition functions. This tends to reduce the intensities of the lines even if the gf values are large. Representative gf values and partition functions are shown in Table 5.

We have no control over the column density a given element within the fireball. On the other hand if we measure the integrated line intensity N_ℓ in absolute units and know all the other parameters we can solve for the column density of material along the line of sight. By making assumptions about the uniformity of distribution of debris within the fireball, and with a knowledge of the size of the fireball at the time the spectrogram was taken we can determine the total amount of the element in vaporized form within the fireball.

NOTE: The above description of how the column density is measured is somewhat simplistic since it assumes an optically thin gas as the source of radiation. HE fireballs with their strong continuum spectrum are optically thick, hence the treatement is more complex. Although the treatment for optically thick sources is more complex it is manageable. The thin gas formulation of the problem was used here to illustrate the basic parameters involved. The same basic parameters enter into the treatment of optically thick sources.

Table 5. Representative Weighted Oscillator Strengths and the Partition Functions for Four Elements.

Species	Partition Function	Wavelength (Å)	Absolute gf Value
Al I	5.9	3944.01	0.23
		3961.52	0.46
Li I	2.1	6707.84	1.51
Fe I	28.5	3719.94	0.37
		4045.81	1.78
U I	54	3584.88	2.4
		3839.62	1.9
		3943.82	0.99

The Boltzman factor contains the temperature of the gas and the excitation energy of the upper state which gives rise to the spectral line; it is extremely important in determining whether any given spectral line can be observed. Table 6 illustrates the importance of the Boltzman factor. A temperature of 2900°K (0.25 ev) was used in this illustration. Values of the Boltzman factor are given in Column 3 for upper energy levels ranging from 2 to 6 ev. Column 4 of the table presents the ratio of the Boltzman factor for each of the upper energy levels to the value of the factor at E_{02} = 3 ev.

When the upper energy level is 4 ev the intensity of a line will be down by a factor of 50 from a line with E_{02} = 3 ev, all other parameters being equal. Similarly when the upper energy level is 5 ev the line intensity will be down by a factor of 3000, again all other parameters being equal.

With the above information for background one may study the spectral lines given in Appendix C and begin to draw conclusions concerning which elements are likely to be observed in HE fireballs and which spectral lines are likely to be the most important. As an example we note that the lithium spectral line at 6707.84 Å should be the most readily observed line for any of the eighteen elements of interest. It has a large gf-value, a small partition function, and the Boltzman factor is greater than that of any of the other lines listed.

Spectroscopic measurements of the streamers appears to be a more formidable task than anticipated. Some mystery still surrounds the results obtained with the intensified ARIES II spectrograph on Event 2. The several frames of spectra which were recorded were very,very weak and appear to be continuum spectra. It is possible through a combination of circumstances that none of the fragments which gave rise to the very bright streamers passed through the field-of-view of the spectrograph during the time that the first two frames were in a position to record. The boresight

Table 6. Values of the Boltzman Factor for Various Upper Energy Levels at kT = 0.25 ev.

1 ev Temperature = 11,605 °K

0.25 ev Temperature = 2,900 °K

E_{02} (ev)	E_{02}/kT (kT = 0.25)	$e^{-E_{02}/0.25}$	$e^{-E_{02}/.25} / e^{-3.0/.25}$
2.0	8	3.35×10^{-4}	54.6
3.0	12	6.14×10^{-6}	1.00
4.0	16	1.13×10^{-7}	1.84×10^{-2}
5.0	20	2.06×10^{-9}	3.36×10^{-4}
6.0	24	3.78×10^{-11}	6.16×10^{-6}

camera record indicates that the fireball entered the field-of-view at around 250 milliseconds. The continuum spectrum we see on the ARIES II record may be that of the late-time fireball and not the streamers. This would explain the continuum appearance of the spectrum.

For possible future use we put forth a model for predicting the spectral characteristics of the streamers. It is based primarily on the behavior of the streamers as observed in the boresight camera record.

The fragments causing the early bright streamers were traveling at Mach 5. One can expect the heavier fragments traveling at that velocity to create a shockwave which heats the air for a short radial distance from the fragment. Simple calculations can show that temperatures in excess of 1000°K can be expected. At the same time the leading edges of the projectile must ablate material due to the heat and air friction. In this model the net result is that the ablated drops from the fragment must be heated to a temperature high enough to combust and radiate molecular oxide emissions. Rapid expansion of the heated air will quickly cool the trail behind the fragment thus shutting off the radiation from the vapor. Air has very poor radiating properties at temperatures lower than 4000°K. Thus one would expect the radiation from the streamer to be entirely that of the ablated material from the fragment.

6. RECOMMENDATIONS

6.1 Program Objectives

The objective of the program was to answer the question whether or not high resolution optical spectroscopy can furnish significant information about the material composition of an HE device by measurement of the fireball spectrum and the spectra of the streamers produced by the high velocity fragments from the exploded device. The results from Event 2 are encouraging but do not conclusively answer the question one way or the other because of instrument limitations and/or the manner in which the instruments were deployed.

We believe that with the information and experience gained on Event 2 a more conclusive answer can be obtained if AFTAC were to conduct a similar program on another HE event. Specific recommendations are made here on how improvements to the experimental measurements may be implemented in the event AFTAC elects to pursue the program objective further.

The program objective has two facets: (1) identification of atomic elements from their characteristic line emissions and, (2) quantitative spectral analysis of the identified species. Because of the nature of the exploding HE device these objectives automatically subdivide further into information to be obtained from fireball spectra and from streamers created by the fragments.

From the limited viewpoint of the experimentalist we have no a-priori knowledge whether one or more of these four subdivisions of the basic objective have higher priority than the others. For the present we shall assume that if another experiment were conducted the instrumentation should be optimized to try and realize the entirety of the objectives.

6.2 Fireball Atomic Emission Spectra

The combined spectral coverage of the fireball on Event 2 by ARIES I and ARIES III spectrographs totaled 355 Å. A study of the spectral

lines listed in Appendix C indicates that optimum coverage of the spectra of those eighteen elements requires a wavelength range at least ten times that amount.

We recommend that the spectral coverage of the fireball be extended to cover the range from 3500 Å to 7000 Å on any future event. Coverage beyond these limits might reach the point of diminishing returns. There are very few strong atomic lines on the long wavelength side of 7000 Å. On the short wavelength side of 3500 Å the excitation energies, therefore the temperature requirement, becomes higher and higher. Also, below 3500 Å atmospheric transmission decreases rapidly and would handicap any long range application of the technique.

Fireball spectral measurements should be made with both high resolution and low resolution instruments. The original argument for using high resolution instruments is still valid; when a strong continuum is present the ability to detect spectral lines increases with improved spectral resolution. (For example, if one instrument has ten times better dispersion than another instrument the continuum intensity as measured by the instrument with high dispersion will be one-tenth that of the other, but the emission line intensifies as measured with both instruments will be the same -- provided the lines are not resolved). The spectral lines of Al and Mn which were observed by ARIES III are broader than the instrumental width of the instrument. This implies that an instrument with somewhat less dispersion would have maintained the same ratio of line to continuum intensities for those particular lines.

The lower the instrument dispersion the more wavelength coverage can be obtained in a single instrument. Thus it is important to experiment in the direction of lower dispersion spectrographs to find the optimum trade-off point between resolution and coverage.

Not all spectral lines will exhibit the behavior of the Al and Mn lines observed on Event 2. The smaller the abundance of the element the narrower the spectral line will be, even for resonance lines. In the survey-type coverage recommended for a possible future test it is equally important to maintain a high resolution capability until the full nature of the spectra is understood.

6.3 Quantitative Analysis of Fireball Spectra

An attempt should be made to perform a quantitative analysis on the spectra obtained on Event 2. The limited number of spectral lines observed will be a handicap because any quantitative analysis rests on a knowledge of the excitation temperature. The excitation temperature is in turn derived from line intensities. If the source is optically thin then in principle only the relative intensities of two lines of the same element are required to determine the excitation temperature (See Appendix D). In practice many lines are used to increase the accuracy of the measurement.

If the source is optically thick, as the case in HE fireballs, the curve-of-growth technique must be used to determine the temperature. The curve-of-growth technique, which was developed by astrophysicists, requires that absolute line intensities be measured. Each atomic element has its own curve-of-growth. Normally many lines of an element are employed, usually the lines of iron, to determine the excitation temperature. One great advantage of the curve-of-growth technique is that it simultaneously determines the column density of the element as well as the temperature. Once the temperature has been determined it is comparitively easy to find the column densities of the other elements from their line intensities, provided one knows which curve-of-growth each of the elements follows.

Relative abundances of materials within the fireball are readily found from the ratios of the column densities. Absolute abundances can be determined only by making assumptions regarding the distribution of materials

within a fireball and a knowledge of the fireball dimensions. The latter can of course be obtained from photographs. A description of the curve-of-growth technique and its application may be found in References 2 and 3.

The manganese lines observed in the ARIES III spectrum were the strongest emission features which were observed on Event 2. (One would expect the two aluminum lines to have been stronger because of the abundance of aluminum in the device, but there are two obvious reasons why they were not: (1) the glass optics of the spectrograph are attenuating severely at those wavelengths and (2) the atomic aluminum is rapidly being oxidized to form Al O. A feeling for the capability of the spectroscopic technique on HE events can be gained from a knowledge of how much manganese was present in the device. Was it perhaps in the aluminum? Type 5456 aluminum if it was present contains 0.5 to 1.0 percent manganese. Or was it in any steel components and if so in what amounts?

On any future experiment if the wavelength coverage extends to 3500 Å many iron lines should appear making an excitation temperature determination comparitively easy. For the analysis of the Event 2 spectra a brightness temperature can first be determined from the continuum spectrum of the fireball. The brightness temperature will set a lower limit to the possible value of the excitation temperature. From the absolute intensifies of the Al, Mn, Fe and Ti lines on the ARIES III record we can iterate using the curve-of-growth technique to possibly find a temperature and those column densities of the four elements which gives a unique solution to the problem.

6.4 Information Content of Streamers

Any conceivable model for the generation of radiating streamers by high velocity fragments of the device leads eventually to the conclusion that the spectra of the streamers should be rich in the atomic or molecular oxide spectrum of the material of which the fragment is composed. Spectra

of the streamers thus become important in many ways: (1) they will identify the composition of the fragments and (2) with a knowledge of the spectral characteristics of the streamers created by fragments with different compositions (e.g. Al and U) one may be able to choose narrow band filters for use with cameras in operational situations for the diagnosis of fragment composition (the filtered camera approach would greatly simplify the problem of devising an operational spectrograph which would record the spectrum of streamers).

We recommend that on any future event intensified spectrographs again be employed to record the spectrum of the streamers. However, we recommend a change in the method of their deployment. The field-of-view of the intensified spectrographs will be widened and located above and/or below the device. The fireball will be excluded from the field-of-view. The vertical field-of-view will be wide enough so that there is a high probability that one or more fragments pass through it.

In a conventional spectrograph the entrance slit width normally defines the width of the spectral lines in the image plane. If the object giving rise to the spectrum is small then one can open up the slit of the spectrograph and let the image formed by the objective lens define the instrumental width of the lines. If the object is small and traveling in a direction perpendicular to the dispersion of the grating then the resulting spectrum at the film plane appears as a customary line spectrum. This approach should give a longer exposure time than the approach used on Event 2 where the streamers traversed the narrow slit of ARIES II in an almost perpendicular direction.

The results of using XR film in the boresight camera lead us to believe that it may be possible to obtain data of some significance from high speed photographic measurements of both the fireball and streamers.

We have illustrated one example of how the pattern of debris within the fireball may give clues as to the original device configuration. We believe that it may also be possible to determine the weight of the fragments which give rise to the streamers with high speed photography using XR film.

To achieve the latter feat we would pursue the following argument:

Slow-down analysis of the fragment using a plot of 1/velocity vs time will readily determine the ballistic coefficient β of any fragment. ($\beta = W/C_DA$, where W is the weight, C_D is the drag coefficient and A is the effective area of the fragment; the slope of the line in a 1/V vs t plot is $\rho g/2\beta$ where ρ is the air density and g is gravitational acceleration).

To determine the weight of a fragment once β is known requires a knowledge of C_DA. We believe that high resolution photography using XR film will give an indication of fragment size and shape in the AFTAC test experiments. Once the fragment size and shape have been estimated it will be possible to form an estimate of C_DA. The argument then is that in the AFTAC test events a correlation can be found between streamer size and C_DA. For an operational situation all that would be required is to measure streamer widths and perform a slowdown analysis to obtain the weight of the fragments.

6.5 Recommended Instrument Plan

The spectrographs we recommend for use on a future experiment are for the most part large strangely-configured instruments. However, they will serve the basic purpose of the experiment, i.e. to determine if the objectives can be achieved. If the results of the measurements are positive the information obatined by these oversize instruments can be used to design compact dedicated instruments for operational situations.

Recommended instrument plans for spectrographs and cameras are presented in Tables 7 and 8. These plans are preliminary and need much refinement prior to any implementation. The plans include only instrumentation which is on hand and available. A nominal amount of modifications and lens adapting would be required. This is customary in tailoring instruments to any experiment.

All lenses specified in the plans are on hand except the 1200mm f/5 lens specified for use with the Photo Sonics 4C camers. Such a lens should be readily available from the Air Force inventory.

The spectrograph plan has weaknesses. Ideally the high resolution coverage of the fireball should extend from 3500 Å to 7000 Å with no gaps. In the present plan the three ARIES instruments must fill the gap between 4500 Å and 7000 Å with only 455 Å of combined coverage. The spectral regions assigned to the ARIES instruments would be based on priorities assigned to the detection of various elements by AFTAC. Other instruments which have been turned back to DoD inventory might fill most of the gaps in the coverage. However, the recommended program already represents a sizable increase in scope and effort. More can always be done but it becomes a matter of budgets and priorities.

Table 7. Recommended Instrument Plan for Spectrographs on a Possible Future Test.

Instrument	Objective Lens	Frame Rate (fr/sec)	Dispersion (Å/mm)	Wavelength Coverage	λ Resolution (Å)	Purpose
REGULUS M-9	30";f/8	Static	5	3200Å-4500Å	0.2	High resolution ultraviolet fireball spectra.
ARIES I	500mm;f/5.5	40	5	120 Å	0.2	High resolution visible fireball spectra in selected wavelength regions.
ARIES II	500mm;f/5.5	40	5.6	135 Å	0.22	
ARIES III	500mm;f/5.5	40	8.3	200 Å	0.33	
BOOTES	300mm;f/2.5	20	80	4200Å-7000Å	3	Low resolution fireball survey spectra
SUPER CYGNUS (Image Intensified)	300mm;f/3	Static	20	4200Å-7000Å	0.8	High resolution streamer spectra
CYGNUS (Image Intensified)	300mm;f/2.5	40	200	4200Å-7000Å	10	Low resolution streamer spectra

Table 8. Recommended Instrument Plan for Cameras on a Possible Future Test.

Instrument	Objective Lens	Frame Rate (fr/sec)	Film Type	Exposure Time (sec)	Spatial Res'ln	Purpose
Photosonics - 4C	1200mm (f/5)	1000	XR	5×10^{-5}	1.5 in	Size, shape and velocity of fragments.
Mitchell HS-100	1000mm (f/10)	100	XR	3×10^{-4}	1.0 in	Dimensions of streamer profiles.
Flight Research IV C	300mm (f/4)	80	XR	4.5×10^{-3}	--	Narrow band filter for 4842A, 4866A Al O bands.
Flight Research IV C	300mm (f/4)	80	XR	4.5×10^{-3}	--	Narrow band filter for uranium oxide bands.
Flight Research IV C	300mm (f/4)	80	XR	4.5×10^{-3}	--	Out-of-band filter for comparison with Al O and UO cameras.

REFERENCES

1. D. F. Hansen and A.H. Tuttle, "High Resolution Spectra of HE Detonations", HSS-B-050, Interim Report on Contract F08606-77-C-0024, 5 January 1979 (U)

2. D. F. Hansen et al, "Quantitative Analysis of High Resolution Optical Spectra", HSS-B-042, Final Report on Contract F19688-77-C-0218/ Visidyne EH8585 HR, May 1978 (Secret).

3. D. F. Hansen et al, "Quantitative Analysis of High Resolution Optical Spectra--Phase II", HSS-B-052, March 1979, Final Report on Contract F19628-78-C-0111, to be published (Secret/RD).

APPENDIX A

INSTRUMENT PLAN FOR EVENT 2

INSTRUMENT PLAN

Prepared By: D. F. Hansen

Operation/Program: Pony Express

Date: 11 June 1979

Event: 2

Station:

Revision No.

Slant Range: 4500 ft

Station Altitude:

Instrument: ARIES I

Purpose:

OBJECTIVE LENS:

Type: Schneider Tele-Xenar

f/n: 5.5 f.l. 500 mm

SPECTROGRAPH SETTINGS

λ coverage 4576 A° to 4710 A°

λ resolution .25 A°

Grating angle setting ______ deg.

Slit width 25 microns;

Height 20 mm

GRATING

Type B&L 35-53-20-530

Grooves 1200 l/mm

Blaze: 1.0μ Order: 2

Dispersion 5.39 A°/mm

AIMING

	Initial	Final
Elev:		
Az:		

Instructions: See Note (1)

FIELD OF VIEW

Horz: ______ deg: Ver: ______ deg.

FILM PRIORITY

	Type	Length
(1)	4XN	35mm x 100 ft(Spec 417)
(2)		
(3)		

EXPOSURE SETTINGS:

Film Type: 4XN

Frame Rate/Speed: 20 fr/sec

Exposure Time: .018 sec

Sector Shutter: 130 deg.

Aperture (f/n.): f/5.5

Special Instructions: Order Sorter W-2A (Only)

PROCESSING

Film Type: 4XN

Developer: AD-500

Time: ______ Temp: ______

Gamma: ______ Exp. Range: ______

SENSITOMETRY:

Sensitometer Type: 157-P1 Scale

Exposure Time: 10^{-2}

Compensator: 10^{-2} + W-94 +ND-0.7

OPERATING PROGRAM

Start: -20 sec. Change: ______ sec.

Rate(1): 20 fps. Rate(3): ______ fps.

Change: ______ sec. Stop: +20 sec.

Rate(2): ______ fps. Marker Rate: ______ pps

COMMENTS & OPTIONS

(1) Center Target on Spectrograph Slit. Use Aiming Light at G. Z. with appropriate offset.

INSTRUMENT PLAN

Prepared By: D. F. Hansen

Operation/Program: Pony Express — Date: 11 June 1979

Event: 2 — Station: — Revision No.

Slant Range: 4500 Ft — Station Altitude

Instrument: ARIES II

Purpose:

OBJECTIVE LENS:
Type: Schneider Tele-Xenar
f/n: 5.5 f.l. 500 mm

SPECTROGRAPH SETTINGS
λ coverage 3940 A° to 4079 A°
λ resolution .25 A°
Grating angle setting ____ deg.
Slit width 25 microns;
Height 20 mm

GRATING
Type B&L 35-53-20-550
Grooves 600 l/mm
Blaze: 1.6 μ Order 4
Dispersion 6.2 A°/mm (Note 2)

AIMING

	Initial	Final
Elev:		
Az:		

Instructions: Aim slit 10 meters to right of target

FIELD OF VIEW
Horz: ____ deg: Ver: ____ deg.

FILM PRIORITY

	Type	Length
(1)	4XN	35mm x 100 ft SPEC 417
(2)		
(3)		

EXPOSURE SETTINGS:
Film Type: 4XN
Frame Rate/Speed: 40 fr/sec.
Exposure Time: .009 sec
Sector Shutter: 130 deg
Aperture (f/n.): 5.5
Special Instructions: Wratten 39 plus Corning CS-4-97 Order Sorter

PROCESSING
Film Type: 4XN
Developer: AD-500
Time: 3.5 ft/min Temp: 75°
Gamma: ____ Exp. Range: ____

SENSITOMETRY:
Sensitometer Type: 157-DT Scale
Exposure Time: 10^{-3}
Compensator: None-(W-94) Filter

OPERATING PROGRAM

Start: -20 sec.		Change: --- sec.	
Rate(1): 40 fps.		Rate(3): --- fps.	
Change: ____ sec.		Stop: +20 sec.	
Rate(2): ____ fps.		Marker Rate: ____ pps	

COMMENTS & OPTIONS
(1) Instrument has been intensified with a 3-stage VARO 8060 electrostatic intensifier; P-20 cathode; P-11 phosphor (2) Intensifier Mag = 0.9

INSTRUMENT PLAN

Prepared By: D. F. Hansen

Operation/Program: PONY EXPRESS
Date: 11 June 1979

Event: 2
Station:
Revision No.

Slant Range: 4500 Ft
Station Altitude

Instrument: ARIES III
Purpose:

OBJECTIVE LENS:
Type: Schneider Tele-Xenar
f/n: 5.5 f.l. 500 mm

SPECTROGRAPH SETTINGS
λ coverage 3944 A° to 4150 A°
λ resolution 0.25 A°
Grating angle setting ____ deg.
Slit width 25 microns;
Height 20 mm

GRATING
Type B&L 35-53-20-560
Grooves 600 l/mm
Blaze: 1.25μ Order: 3
Dispersion 8.3 A°/mm

AIMING

	Initial	Final
Elev:		
Az:		

Instructions: See Note (1)

FIELD OF VIEW
Horz: ____ deg: Ver: ____ deg.

FILM PRIORITY

	Type	Length
(1)	4XN	35mm x 100 ft (SPEC 417)
(2)		
(3)		

EXPOSURE SETTINGS:
Film Type: 4XN
Frame Rate/Speed: 20 fr/sec
Exposure Time: .018 sec
Sector Shutter: Note (2)
Aperture (f/n.): f/5.5
Special Instructions: Schott BG-37 Order Sorter Filter

PROCESSING
Film Type: 4XN
Developer: AD-500
Time: ____ Temp: ____
Gamma: ____ Exp. Range: ____

SENSITOMETRY:
Sensitometer Type: 157 P1 Scale
Exposure Time: 10^{-2}
Compensator: 10^{-2} + W94 + ND 0.7

OPERATING PROGRAM

Start: -20 sec.	Change: — sec.
Rate(1): 20 fps.	Rate(3): — fps.
Change: — sec.	Stop: +20 sec.
Rate(2): — fps.	Marker Rate: — pps

COMMENTS & OPTIONS
(1) Center target on Spectrograph Slit. Use Aiming Light at G. Z. with appropriate offset.

(2) Sector Shutter removed.

Best Available Copy

INSTRUMENT PLAN

Prepared By: D. F. Hansen

Operation/Program: PONY EXPRESS — Date: 11 June 1979

Event: 2 — Station: — Revision No.:

Slant Range: 4500 ft — Station Altitude:

Instrument: BORESIGHT CAMERA - Flight Research IV-C

Purpose:

OBJECTIVE LENS:
Type: Nikkor
f/n: 5.0 f.l. 500 mm

SPECTROGRAPH SETTINGS (N A.)
λ coverage ____ A° to ____ A°
λ resolution ____ A°
Grating angle setting ____ deg.
Slit width ____ microns;
Height ____ mm

GRATING (N. A.)
Type
Grooves ____ l/mm
Blaze:
Dispersion ____ A°/mm

AIMING See Note (1)

	Initial	Final
Elev:		
Az:		

Instructions: Take Set-up photographs on B&W film.

FIELD OF VIEW
Horz: ____ deg: Ver: ____ deg.

FILM PRIORITY

	Type	Length
(1)	~~XR~~ - SO-184	35mm x 100 ft
(2)	4XN	35mm x 100 ft
(3)		

EXPOSURE SETTINGS:
Film Type: SO-184 (XR)
Frame Rate/Speed: 40 fr/sec
Exposure Time: 0.009 sec
Sector Shutter: 130 deg.
Aperture (f/n.): f/5
Special Instructions: W-12

PROCESSING
Film Type: SO-184
Developer: C-22
Time: — Temp: —
Gamma: — Exp. Range: —

SENSITOMETRY:
Sensitometer Type: 157-DT Scale
Exposure Time: 10^{-2} + 10^{-3} sec
Compensator: No Comp (W-94)

OPERATING PROGRAM
Start: -20 sec. — Change: — sec.
Rate(1): 40 fps. — Rate(3): — fps.
Change: — sec. — Stop: +20 sec.
Rate(2): — fps. — Marker Rate: — pps

COMMENTS & OPTIONS
(1) Center F.O. V. on target.

APPENDIX B

XR FILM CHARACTERISTICS

APPLIED PHOTO SCIENCES, INC.

NEEDHAM HEIGHTS, MASS. 02194

XR EXTENDED RANGE FILM

A multilayer black and white negative film, for use over an extreme range of exposure. It is available in motion picture film, sheet film, in 35mm cartridges, and as aerial film.

APPLICATIONS

XR Film is ideally suited for photography where the light conditions during exposure are unpredictable or where the subject exhibits a brightness range that varies over enormous limits. It has been used successfully in nuclear and non-nuclear explosions, rocket exhaust tests, laser photography, abortive missile launching, oscillography and other similar applications.

GENERAL DESCRIPTION

XR Film has three layers, all of which are panchromatically sensitized. The emulsion layers from top to bottom respectively are high speed, medium speed and low speed. Incorporated in the emulsion layers are dye forming couplers which react simultaneously during development to produce a separate dye image along with a silver image in each layer. The silver images are removed by bleaching, leaving only dye images of yellow, magenta and cyan respectively.

EXAMINATION OF NEGATIVES

A filter is not required to view XR film. The yellow image can be seen in white light with no filter but it has poor contrast. It has good contrast with a blue filter. Satisfactory Kodak Wratten Filters are Blue Nos. 47 or 47B, Green No. 61, and Red No. 25. The choice of filter for XR is not very critical—other similar color separation filters will do nearly as well.

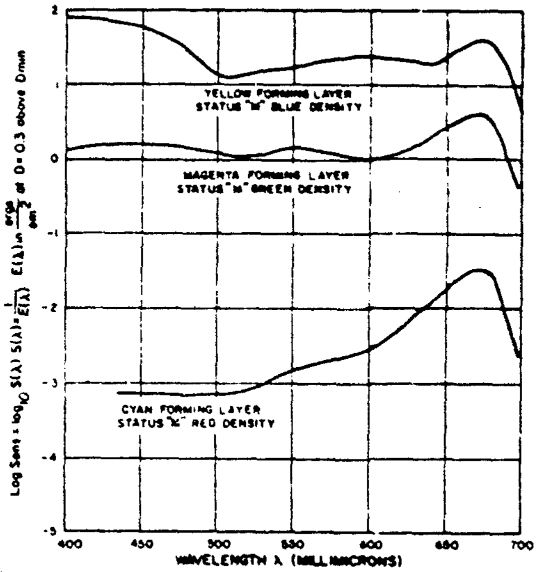
EXPOSURE INDEX

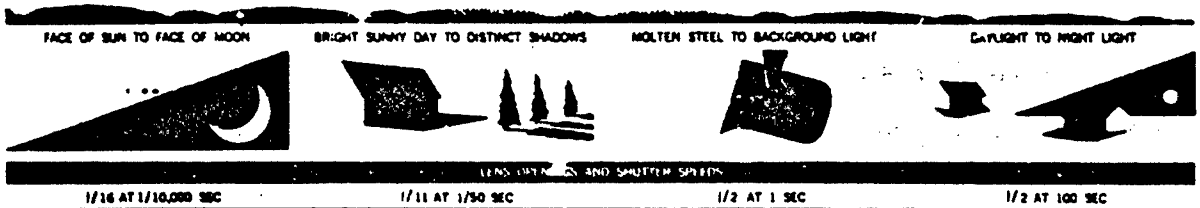
Fast Layer	400
Medium Speed Layer	10
Slow Layer	.004

These settings are recommended for meters marked for American Standard Exposure Indexes. It is virtually impossible to overexpose the slow layer in most applications. The user should take advantage of this characteristic and not risk underexposure. Note that XR is not an extremely fast film; if exposure conditions are so poor that only the fast layer is exposed, a more conventional film would do as well.

COLOR SENSITIVITY: Panchromatic

SPECTRAL SENSITIVITY: Sensitivity is the reciprocal of exposure (ergs/cm^2) required to produce a given density above the minimum value for each color image.





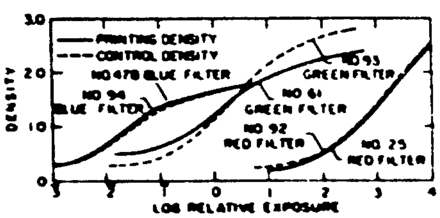
EXPOSURE GUIDE TABLE

RESOLUTION

Fast Layer	70 lines/mm
Medium Speed Layer	50 lines/mm
Slow Layer	30 lines/mm

D-LOG E CURVES

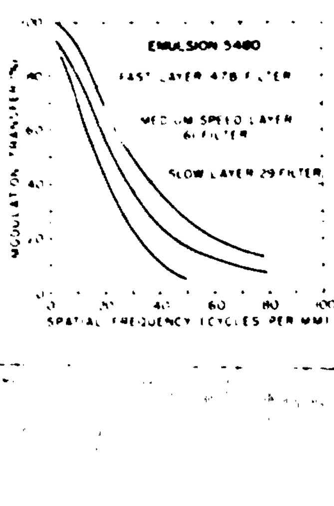
The curves show typical density vs. log exposure data from a 10^{-3} sec xenon flash exposure, and with normal C-22 processing. Densities as measured with a 3-color transmission densitometer are shown as dotted lines while printing densities through the recommended printing filters are shown as solid lines.



MODULATION TRANSFER FUNCTION

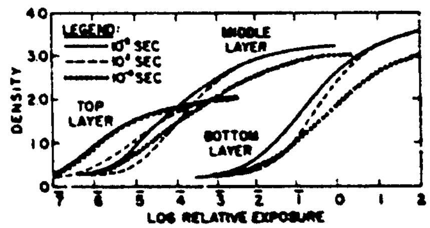
The modulation-transfer characteristics of a film indicate the effects that diffusion of light within the emulsion will have on the microstructure of the image. Image detail characteristics of a film used with an optical system may be predicted from the separate modulation-transfer functions for the film and the optical system.

The data is from a white-light exposure. The images were scanned with Wratten filter numbers 47B, 61 and 29 respectively for the fast, medium speed, and slow layers.



RECIPROCITY FAILURE

Changes in speed or contrast or both occur with extremely short or extremely long exposure times. The curves show these changes for exposure times of 10^{2}, 10^{-2}, and 10^{-6} sec.



SAFELIGHT HANDLING

Total darkness required.

PROCESSING

XR Film may be processed to produce a color-coded negative or positive image. Kodak Color Processing Kit, Process C-22, contains all the chemicals for preparing a complete set of processing solutions. Developing time in the C-22 process is the same as that for Kodacolor and results in a negative. Processing in Kodak Color Kit E-2, E-3 will produce a direct reversal positive.

PRINTING

Black and white positive prints are made from XR Film in a manner similar to that used to make color separations from color films, since the dyes in XR film are very similar to those in color film. The fast layer of XR film has a coarser grain pattern than the slow layer, which has a fine pattern. Therefore, in making prints, the user should anticipate that the grain pattern will vary from layer to layer and that prints made from an XR film that is predominantly the top (fast) layer will be more grainy than prints made from the bottom (slow) layer. A broad range of composite prints, showing detail from two or more layers in a single frame, can be made by conventional dodging techniques using the appropriate color filters.

APPENDIX C

TABLE OF THE STRONGEST SPECTRAL LINES OF INTEREST FOR EIGHTEEN ELEMENTS

INTENSITY CHARACTERIZATIONS

MIT Wavelength Tables

For the neutral atom the most sensitive line (raie ultime) is indicated by U1, and other lines by U2, U3 in order of decreasing sensitivity. Not all elements are so classified in the MIT Wavelength Tables.

NBS - Monograph 145

Intensities are based on measurements in a copper arc operated at 6000°K. The author has replaced the numerical relative intensity values given in this monograph by S1, S2, etc. to correspond to the decreasing order of sensitivity as is done in the MIT Wavelength Tables. This classification is used by the author primarily when the MIT Wavelength Tables do not classify the sensitivities of lines for an element, or when the most sensitive lines fall outside of the possible range of useful wavelengths in this program.

SPECIES	WAVELENGTH (Å)	SENSITIVITY	ENERGY LEVELS LOWER (ev)	UPPER (ev)
Al I	3944.01	U2	0.00	3.14
	3961.52	U1	0.01	3.14
Be I	2348.61	U1	0.00	5.28
	4572.66		5.28	7.99
Cd I	2288.02	U1	0.00	5.42
	3261.06		0.00	3.80
Cr I	4254.35	U1	0.00	2.91
	4274.80	U2	0.00	2.90
	4289.72	U3	0.00	2.89
	4344.51		1.00	3.86
	4351.77		1.03	3.88
	4646.17		1.03	3.70
	5204.52	U6	0.94	3.31
	5206.04	U5	0.94	3.31
	5208.44	U4	0.94	3.31
Cu I	[illegible].54	U1	0.00	3.82
	[illegible]3.96	U2	0.00	3.79
	5105.54	U5	1.39	3.82
	5700.24		1.64	3.82
	5782.13		1.64	3.79
Gd I	3783.05	S2	0.12	3.40
	4053.64		0.12	3.18
	4058.22		0.03	3.08
	4078.70	S3	0.07	3.11
	4175.54		0.21	3.19
	4225.85	S1	0.21	3.15

SPECIES	WAVELENGTH (Å)	SENSITIVITY	ENERGY LEVELS LOWER (ev)	UPPER (ev)
Fe I	3719.94	U1	0.00	3.33
	3737.13	U2	0.05	3.37
	3745.56	U3	0.09	3.40
	3745.90	U5	0.12	3.43
	3748.26	U4	0.11	3.42
	3820.43		0.86	4.10
	3859.91		0.00	3.21
	4045.82		1.48	4.55
La I	5455.15	U3	0.13	2.40
	5930.65	U2	0.13	2.22
	6249.93	U1	0.51	2.49
Pb I	2833.06		0.00	4.38
	3639.58		0.97	4.38
	3683.48	U2	0.97	4.33
	4057.83	U1	1.32	4.38
Li I	3232.61	U2	0.00	3.83
	4602.86	U4	1.84	4.54
	6103.62	U3	1.85	3.88
	6707.84	U1	0.00	1.85
Mg I	2852.13	U1	0.00	4.34
	3829.35	U4	2.71	5.94
	3832.30	U3	2.71	5.94
	3838.26	U2	2.72	5.94
	5167.34		2.71	5.11
	5172.70		2.71	5.11
	5183.62		2.72	5.11

SPECIES	WAVELENGTH (Å)	SENSITIVITY	ENERGY LEVELS LOWER (ev)	UPPER (ev)
Mn I	4030.76	U1	0.00	3.08
	4033.07	U2	0.00	3.07
	4034.49	U3	0.00	3.07
	4035.73		2.14	5.21
Ti I	3635.46	U2	0.00	3.41
	3642.68		0.05	3.88
	3653.50		0.05	3.44
	3752.86		0.05	3.35
	3948.67		0.00	3.14
	3956.34		0.02	3.15
	3958.21		0.05	3.18
	3981.76		0.00	3.11
	3989.76		0.02	3.13
	3998.64		0.05	3.15
	4305.92		0.85	3.73
	4533.24		0.85	3.58
	4981.73	U1	0.85	3.34
W I	4008.75	U3, S1	0.37	3.46
	4074.36	S2	0.37	3.41
	4294.61	U2	0.37	3.25
	4302.11	U1	0.37	3.25
U I	3489.37	S4	0.00	3.55
	3514.61	S5	0.00	3.53
	3550.82	S7	0.00	3.49
	3561.80	S8	0.00	3.49
	3566.60	S2	0.08	3.55

SPECIES	WAVELENGTH (Å)	SENSITIVITY	ENERGY LEVELS LOWER (ev)	UPPER (ev)
U I	3584.88	S1	0.00	3.46
	3659.16	S12	0.08	3.46
	3812.00	S3	0.00	3.25
	3839.62	S9	0.00	3.48
	3871.04	S6	0.00	3.20
	3943.82	S10	0.00	3.14
	4042.76	S11	0.08	3.14
	4153.97	S13	0.00	2.98
Yb !	3464.37	S1	0.00	3.57
	3987.99	S2	0.00	3.11
Zn	3075.90		0.00	4.03
Zr	3519.60	U3	0.00	3.52
	3547.68	U2	0.07	3.56
	3601.19	U1	0.16	3.60
	3835.96		0.00	3.23
	3863.87		0.07	3.28
	3885.42		0.00	3.19
	3890.32		0.15	3.34
	3929.53		0.01	3.23
	4687.80	U4	0.73	3.37

APPENDIX D

Excitation Temperature Determination For an Optically Thin Source

The classic method of determining excitation temperature of a hot gas uses the relative integrated intensities of spectral lines from atoms in the same stage of ionization. The underlying assumptions are that the excited levels of the atoms are populated according to the Boltzmann distribution, that the gas is thin to the radiation of the lines, and that the gas is uniform in temperature. Since the mathematical formulation to be given below contains the excitation energy of the upper state of the line, the accepted practice is to call the result the excitation temperature.

The radiant power density emitted by a spectral line from a small volume of hot gas is

$$p_{21} = n_2 A_{21} (h\nu)_{21} \times 10^{-7}, \text{ watts cm}^{-3} \qquad \text{D.1}$$

where the upper and lower energy levels are designated 2 and 1 respectively, n_2 is the number density of atoms in the upper level, A_{21} is the Einstein A coefficient for the transition, and $(h\nu)_{21}$ is the photon energy. To find the integrated line intensity which is measured by the spectrograph, the power density is multiplied by the thickness, L, of the gas column in the observation direction and divided by 4π. The resulting quantity is the integrated radiance in the line which is

$$N_\ell = p_{21} L/4\pi, \text{ watts cm}^{-2} \text{ ster}^{-1}$$

$$= n_2 L A_{21} (h\nu)_{21} /4\pi \times 10^{-7} \qquad \text{D.2}$$

To obtain a more explicit formula, the following substitutions are made. For the number density of atoms in the upper state, one can

substitute the expression

$$n_2 = n_0 (g_2/U) \exp(-E_{02}/kT) \text{ atoms cm}^{-3} \qquad \text{D. 3}$$

where n_0 is the number density of atoms in the ground state, g_2 is the statistical weight of the upper level, U is the partition function of the neutral atom, E_0 is the energy of the upper level above the ground level, k is Boltzmann's constant, and T is the temperature in degrees Kelvin. For A_{21}, one can write

$$A_{21} = 3\gamma_{cl} (gf)/g_2, \text{ transitions sec}^{-1} \qquad \text{D.4}$$

with the classical damping coefficient written as

$$\gamma_{cl} = 8\pi^2 e^2/3mc\,\lambda^2 \qquad \text{D. 5}$$

When all of these quantities are substituted into Eq. 4.2 and frequency is converted to wavelength in angstroms, the result is

$$N_\ell = 1.054\,(gf) \exp(-E_{02}/kT)\,[n_o L/U]/\lambda^3 \text{ w cm}^{-2}\text{ sr}^{-1} \qquad \text{D. 6}$$

Next, this expression is rearranged to give

$$N_\ell \lambda^3/(gf) = 1.054\,[n_o L/U] \exp(-E_{02}/kT) \qquad \text{D. 7}$$

Taking the common logarithm of both sides of the equation results in

$$\log[N_\ell \lambda^3/(gf)] = \log[1.054\, n_o L/U] - (5040/T)\, E_{02}$$
$$= A - (5040/T)\, E_{02} \qquad \text{D. 8}$$

where E_{02} is in electron volts (ev). A plot of $N_{\ell} \lambda^3/gf$ vs E_{02} should be a straight line since it is of the simple linear form Y = mX +b. By equating the measured line slope to the factor (-5040/T), the excitation temperature can be determined. From the constant A, the column density of ground state atoms can be found when the partition function is known.

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